**US Army Corps
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Waterways Experiment
Station

Use of Activated Carbon for the Treatment of Explosives-Contaminated Groundwater at the Picatinny Arsenal

by   R. Mark Bricka, Elizabeth C. Fleming

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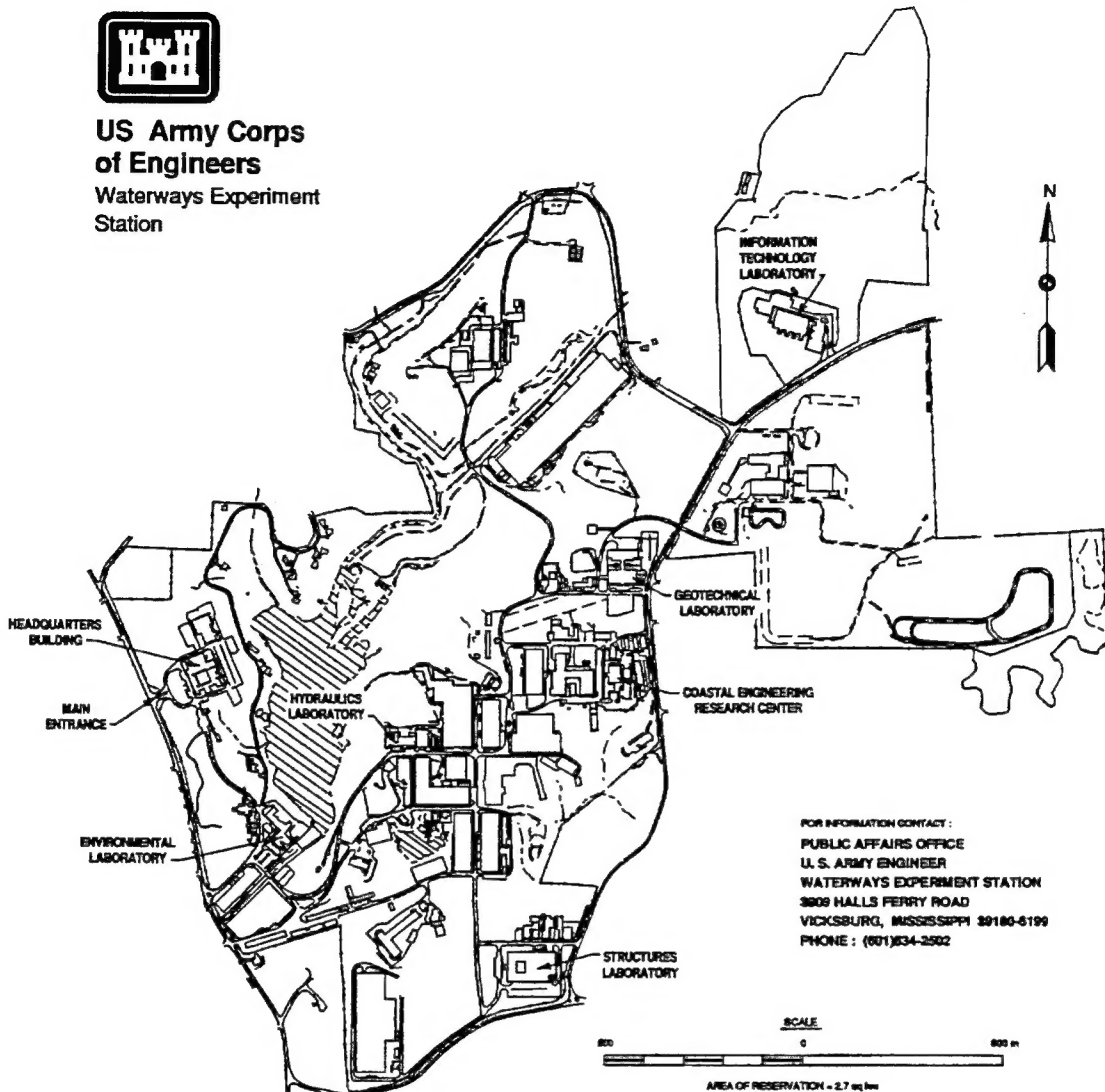3909 Halls Ferry Road
Vicksburg, MS   39180-6199

Final report

**US Army Corps
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STRUCTURES
LABORATORY

SCALE

800   0   800 m

AREA OF RESERVATION = 2.7 sq km

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Preface

This report is the second report in a two-part series. The first report, "Ultraviolet/Chemical Oxidation Treatment of RDX-Contaminated Waters at the Picatinny Arsenal," details a study conducted to evaluate the effectiveness of ultraviolet/chemical oxidation on drinking water at Picatinny Arsenal. This report details work conducted to evaluate the effectiveness of granular activated carbon to treat the same water.

This report should be cited as follows:

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
feet	0.3048	meters
gallons (U.S. liquid)	3.785412	liters
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms

1   Introduction

Background

Picatinny Arsenal, officially known as the U.S. Army Armament Research, Development and Engineering Center (ARDEC), is located approximately 40 miles[1] west of New York City, New York, near the city of Dover in Rockaway Township, Morris County, New Jersey (Figure 1). The Picatinny Arsenal (PTA) land area consists of 6,491 improved and unimproved acres. Green Pond Brook flows the length of PTA. There are two major lakes located within the arsenal: Lake Denmark and Picatinny Lake (Figure 2). As a result of erosion, PTA is characterized by rather significant relief bounded to the northwest by Green Pond Mountains and Copperas Mountains and an unnamed ridge to the southeast (Figure 2). Most of the PTA buildings and other facilities are located on the narrow valley floor or on the slopes along the southeast side of the arsenal.

Site History

The current PTA was originally established by the U.S. War Department during the late 1870s as the U.S. Powder Depot. Five magazines, officers' quarters, service building, and stables were built and operated merely as a storage and powder depot for more than a decade. Around 1903, PTA's mission expanded to include the assembly of powder charges for cannons and the filling of projectiles with maximite (a propellant). Sodium nitrite and high explosives were also stored at the arsenal during this period (Benioff et al. 1991; Dames and Moore 1991).

Operations expanded to include powder production, and in 1907 the U.S. Powder Depot became PTA. With the outbreak of World War I (WWI), PTA begin producing all sizes of projectiles (from 0.30 caliber to 16 in.). In the years following WWI, operations consisted of melt-loading of projectiles and the manufacture of pyrotechnic signal flares (War Plans Division 1931).

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[1]   A table of factors for converting non-SI units of measurement to SI units is presented on page xi.
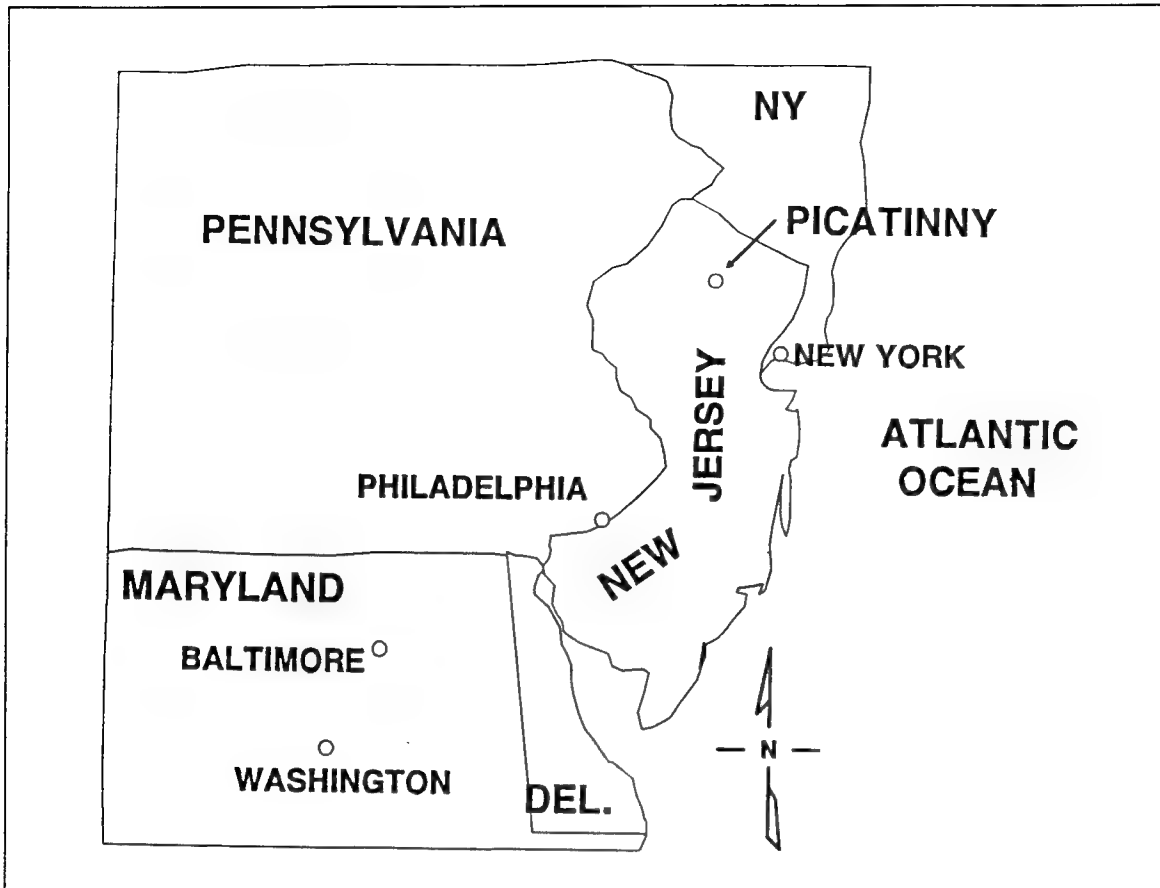
Figure 1.   Picatinny Arsenal location

During World War II (WWII), the operations at PTA were expanded to large-scale ammunition production. These operations included the production of artillery ammunition, bombs, high explosives, pyrotechnics, and other ordnance. After WWII, PTA's operations were scaled back with the primary role being that of research and development of new ordnances. PTA's mission as a large-scale ammunition production facility was reactivated during the Korean and Vietnam conflicts. Table 1 details the amount of explosives produced at PTA from 1943 - 1970.

Today, PTA's primary mission is oriented towards research and development of conventional weapons. These efforts include missile warhead programs, aircraft weaponization, rocket-assisted projectiles, tank weaponry, flare development, and similar projects.

One significant event that should be discussed occurred at PTA on July 10, 1926. Lightning struck a tree overhanging a magazine at the adjacent Naval Powder Depot at Lake Denmark. The detonation of the depth bombs stored in that magazine set off two neighboring magazines. This resulted in a massive explosion that devastated much of the PTA and killed 18 people.
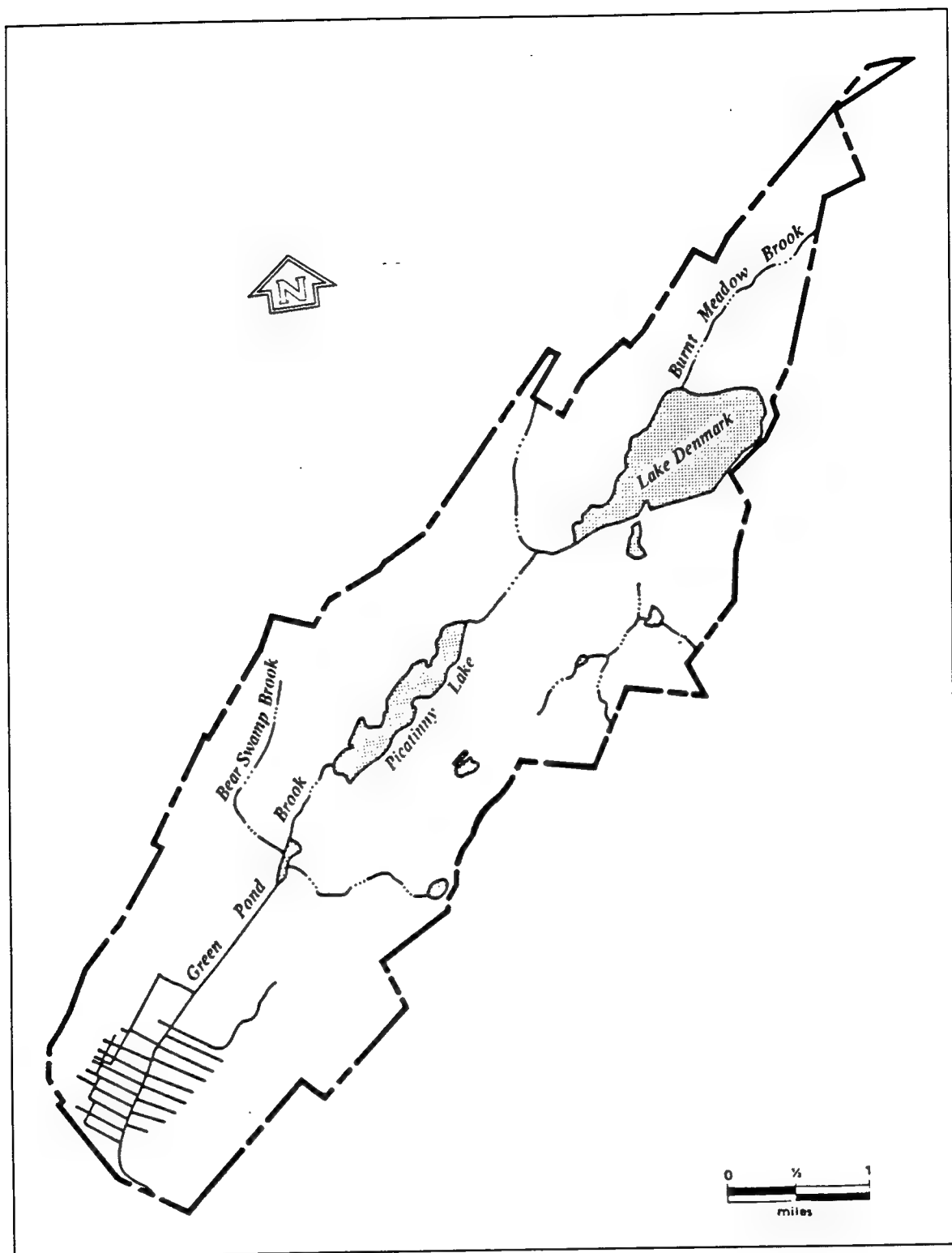
Figure 2.   Map of Picatinny Arsenal (source: Dames and Moore 1991)

Table 1

Annual Amounts of Explosives Produced at Picatinny Arsenal from 1943 to 1970 (lb/year)[1] (Source: USATHAMA 1976)

Explosive Materials[2]	1943	1944	1949	1950	1951	1952	1953	1954	1955
Smokeless powder	7,920,000	6,150,000		1,100,000	40,000	28,089			
Tetryl	1,536,000	1,080,000							
EDNA	12,000	10,000							
Boosters	2,820,000	1,400,000							
Primers	7,430,000	5,250,000							
Detonators	25,550,000	11,609,000							
Demolition blocks				10,000					
C-4 composition				800,000	600,000				
T-9 composition			1,900,000	1,720,000					
Igniters M-20			300,000	180,000	1,320,000	1,200,000			
60-mm mortar prop. powder					120,000	120,000			
Solvent powder							140,000	138,000	240,000
Nitroglycerin					78,000	80,000	75,000	82,000	100,000
Solventless powder									1,800,000
Other H.E.					6,400	6,200	143,000	246,000	2,040,000
P & E misc.									28,000

Explosive Materials[2]	1956	1957	1958	1959-60	1961-62	1963-64	1965-66	1968-70
Nitroglycerin	98,000	102,000	95,000	90,000	92,000	95,000	88,000	80,000

[1] No production reported for 1945-1948.
[2] Only nitroglycerin produced during the period 1956 through 1970.
Source: Benioff et al. 1991.

Area of Interest

As a result of the munitions production at PTA, the land and groundwater have become contaminated with various chemicals. Between 1976 and 1989, the PTA and the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA), now the U.S. Army Environmental Center (AEC), identified 156 remedial investigation sites at the arsenal (Benioff et al. 1991). Seventeen of these sites are located in Area F (the propellant area) at PTA, distributed over 86 acres (Figure 3). Facilities located in Area F were used for processing, mixing, handling, and storage of propellants.

The drinking water supply at PTA is obtained from three wells: Well 410, Well 430A, and Well 129. Two of the three wells (Well 410 and 430A) are located in Area F (Figure 3). In the 1980s, sampling of these wells revealed low-level contamination of military explosives: RDX and HMX. Trace levels of 1,2 dichloroethane (1,2 DCE), trichloroethylene (TCE), chlorobenzene, and benzene were also found in Well 410, but the only regulated volatile compound showing presence in recent years is TCE. Well 430A is reported to be free of contamination by volatile organic compounds. While Well 430A is contaminated with explosives (typical RDX and HMX concentrations of 1 to 3 ppb and < 1.5 ppb, respectively, are reported), the concentration levels are less than those found in Well 410 (Foster Wheeler Enviresponse, Inc. 1990). Consequently, this study focuses on the treatment of water from Well 410. Table 2 presents historical sampling and analysis from Well 410.

Site 138 in Area F is located near the intersection of Sixteenth Avenue and Ninth Street in the Green Pond Brook Valley (Figure 4). Well 410 is located on Site 138. Contamination at Site 138 is primarily attributed to the activities conducted in Buildings 404, 407, and 408 (Figure 4). Activities conducted in these buildings are listed below (Dames and Moore 1992):

a. Building 404. Used as a chemical laboratory reportedly used to test-burn propellants.

b. Building 407. Used as a chemical laboratory and later used as an energetic laboratory where propellants were manufactured.

c. Building 408. Used as a nitration building and later used for explosives metal casting and chemical synthesis operation. Presently, this building is used for chemical storage.

Although a mechanism for the contaminant transport to groundwater has not been positively identified, a report conducted by Foster Wheeler Enviresponse, Inc. (1990) attributes the contamination of Well 410 to the activities conducted at Site 138.

F-F'   Location of Geologic Cross-Section
        Across Area F
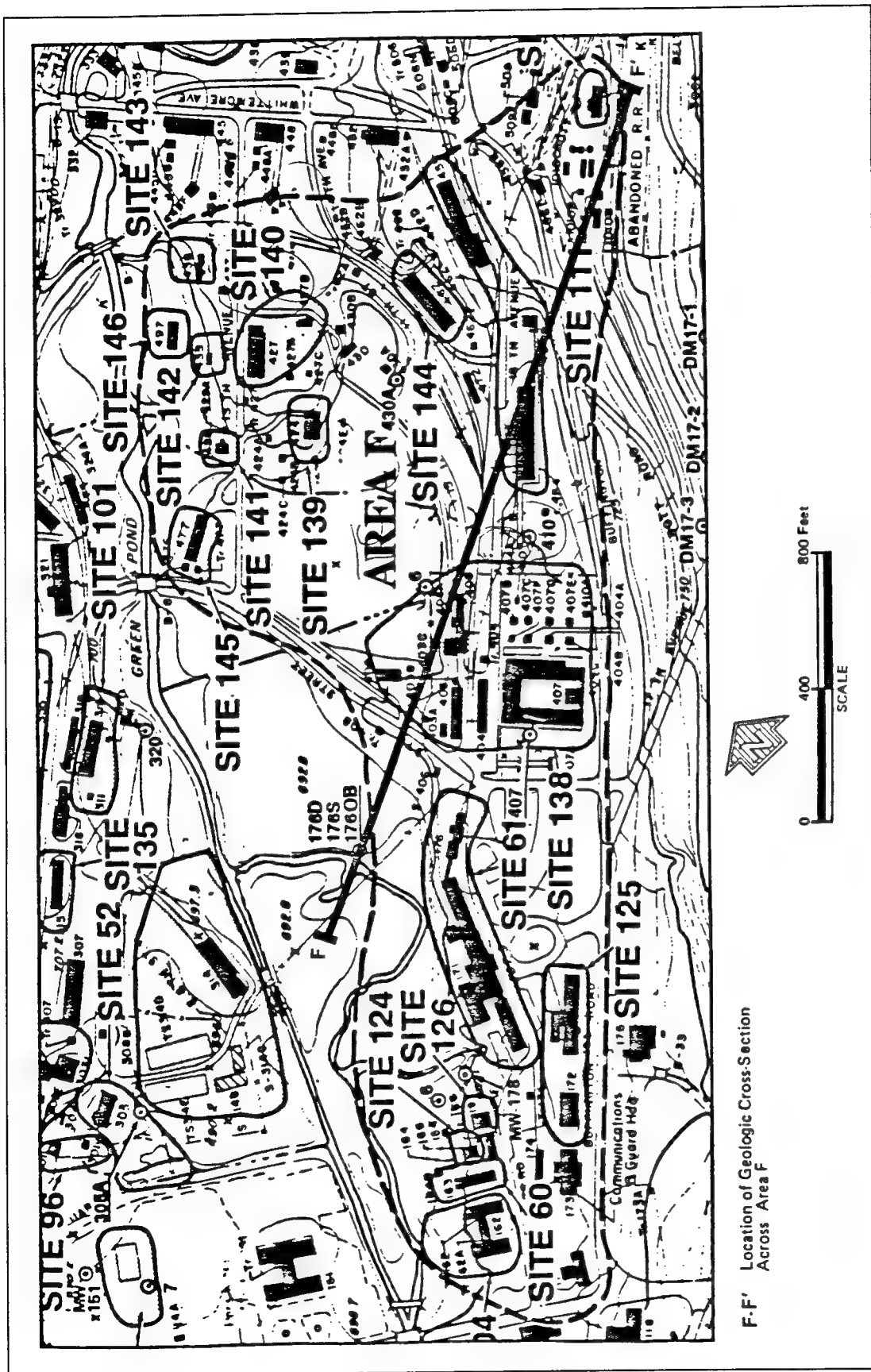
Figure 3.   Area F at Picatinny Arsenal (source: Dames and Moore 1992)

Table 2
Historical Sampling of Well 410 at Picatinny Arsenal (Source: Dames and Moore 1992), µg/ℓ

Detected Compounds	CHCL3	12DCLE	BRDCLM	12DCLP	TCE	CHBR	CH2CL2	T12DCE	CCL4	111TCE	DBRCLM	CLC6H5	12DCLB	C6H6	MEC6H5	CH3CL
Available Standards	100	5	100	5	5			100	5	200				5	1,000	100
		10			1				2	26		4		1		
Dates:																
8/31/89		15.3			4.89											
9/7/89					7.64											
9/22/89					3.6											
9/27/89					3.5											
10/10/89					4											
10/18/89					8.99											
10/25/89					7.33											
11/2/89				1.22	7.31											
11/8/89					4.39											
11/14/89					6.68											
11/29/89					4.63											
12/5/89					4.12											
12/12/89					5.49											
12/20/89				2.48	2.90		8.37	3.27								
12/22/89					1.77		3.33									
12/27/89					5.0		15.7									

(Sheet 1 of 4)

Note: Source: IRDMS. Key to compound abbreviations: CHCL3 - Tri-chloromethane; 12DCLE - 1,2-Dichloromethane; BRDCLM - Bromodichloromethane; 12DCLP - 1,2-Dichloropropane; TCE - Trichloroethene; CHBR - Bromoform; CH2CL2 - Methylene Chloride; T12DCE - trans 1,2-Dichloroethane; CCL4 - Carbon Tetrachloride; CH3CL - Chloromethane; 111TCE - 1,1,1-Trichloroethane; DBRCLM - Dichlorobromomethane; CLC6H5 - Chlorobenzene; 12DCLB - 1,2-Dichlorobenzene; C6H6 - Benzene; MEC6H5 - Toluene. NA = Not analyzed; ND = Not detected.

Table 2 (Continued)

Detected Compounds Dates:	CHCL3	12DCLE	BRDCLM	12DCLP	TCE	CHBR	CH2CL2	T12DCE	CCL4	111TCE	DBRCLM	CLC6H5	12DCLB	C6H6	MEC6H5	CH3CL
1/4/90					8.1											
1/11/90					8.4											
1/18/90			1.39	1.98												
4/5/90					4.37											
4/10/90					13.1											
4/17/90					8.40											
5/17/90					8.6											
5/22/90				1.1	4.16											
3/6/91					3.0											
3/20/87					2.1											
3/27/87	30				2.2	7.4										
3/28/89					6.3											
4/13/87					2.0											
3/16/88					1.0											
12/27/88	3.4		4.4								2.9					
1/11/89												124	245	46.9		
1/18/89	2.4				3.1					1.0						
1/25/89					5.9											
2/15/89					3.0										3.2	
2/22/89					2.8				1.0							18.4
2/28/89					3.4										3.8	
3/15/89					7.4											

Table 2 (Continued)

Detected Compounds	CHCL3	12DCLE	BRDCLM	12DCLP	TCE	CHBR	CH2CL2	T12DCE	CCL4	111TCE	DBRCLM	CLC6H5	12DCLB	C6H6	MEC6H5	CH3CL
Dates:																
3/22/89					7.1										1.0	
4/5/89					6.8											0.6
4/11/89					5.5											
4/18/89				4.6												
5/2/89					6.7											0.5
5/5/89	1.3	1.0			5.2									3.8		
5/9/89					6.3											0.5
5/24/89		1.1			10.4											
5/30/89					9.5											
6/7/89					10.0											
6/15/89					11.6											
6/21/89					9.3											
6/27/89					9.9											
7/6/89	1.4				10.0											
7/11/89	1.8				13.6											
8/3/89		9.38														
8/9/89					5.77											
8/17/89										4.4						
8/23/89					5.6											

(Sheet 3 of 4)

Table 2 (Concluded)

Analyte µg/ℓ	Date							
	06/25/90	07/05/90	08/16/90	08/30/90	09/28/90	10/23/90	11/28/90	05/23/91
HMX	ND	ND	1.964	ND	2.082	ND	1.781	NA
Nitrocelluose	NA	NA	NA	NA	NA	NA	NA	515/1,060
RDX	6.099	5.57	6.134	4.454	5.699	4.771	6.334	NA

(Sheet 4 of 4)
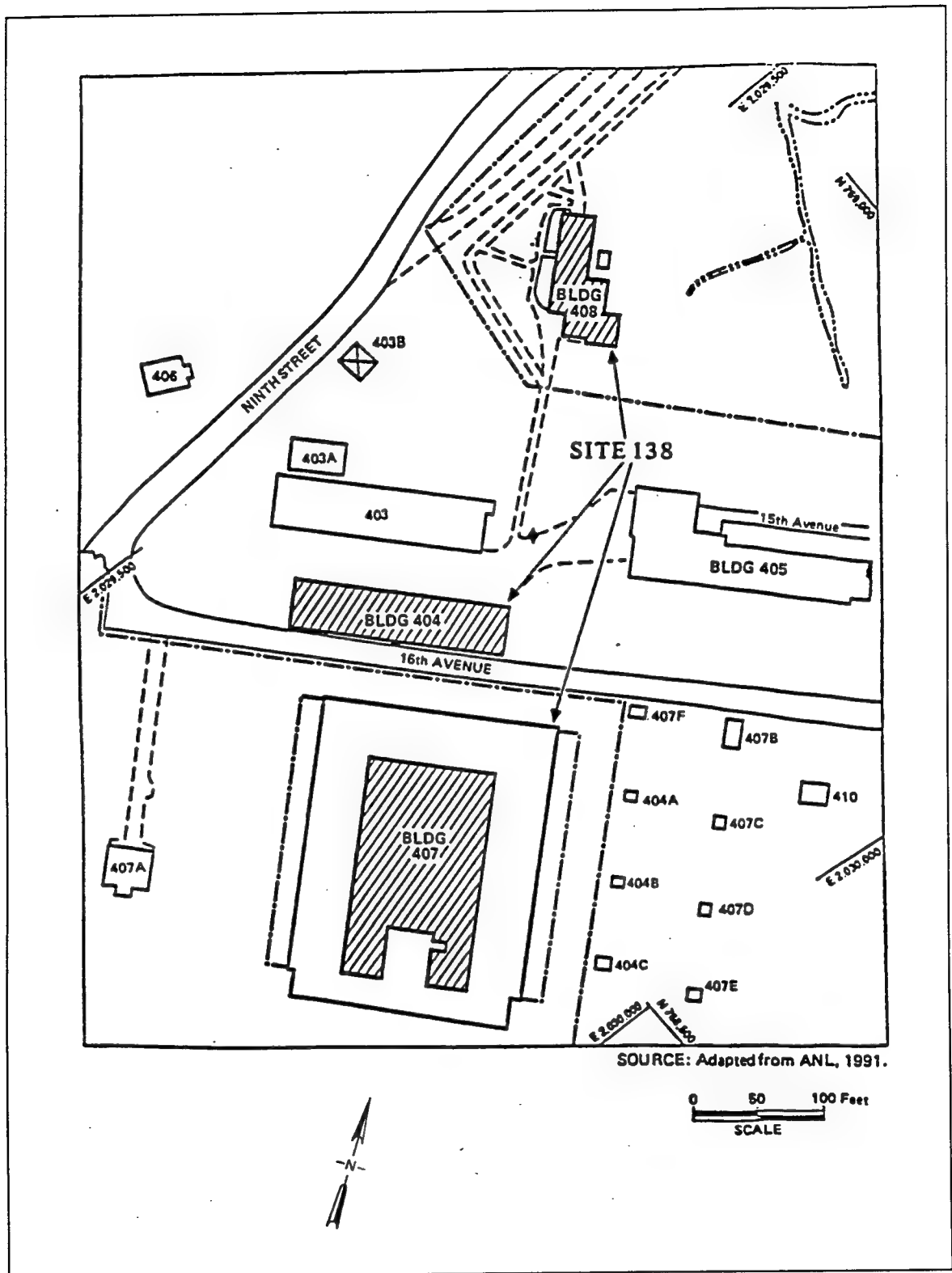
Figure 4.   Site 138 in Area F at Picatinny Arsenal (source: Dames and Moore 1992)

Contaminants of Interest

Although Well 410 is contaminated with explosives and volatile organic compounds, this study focuses on the explosive contamination. Background information on the two explosives of concern (RDX and HMX) is presented in the following sections.

RDX

RDX (Hexahydro-1,3,5-trinitro-1,3,5-triazine) is a code name for Research Department Explosive or Royal Demolition Explosive. RDX is described as a white crystalline solid with about 1.3 times the explosive power of trinitrotoluene (TNT) (Sullivan et al. 1979). RDX has been extensively used as a high-impact explosive in military munitions formulations during and since World War II. RDX is also used as a rat poison (American Conference of Governmental Industrial Hygienists (ACGIH) 1986; Windholz 1983). RDX is generally manufactured by the nitration of hexamethylene tetramine ($C_6H_{12}N_4$). The product from RDX production generally contains 9-percent HMX. RDX has a low-water solubility (7.6 mg/ℓ at 25 °C). Other properties of RDX are listed in Appendix A.

RDX is classified as an EPA Group C compound: Possible Human Carcinogen. The U.S. Environmental Protection Agency's (USEPA) lifetime health advisory for RDX is set at 0.002 mg/ℓ (2 ppb) for adults and was determined based on a drinking water equivalent level (DWEL) of 0.1 mg/ℓ. The DWEL is based on a reference dose (RfD) of 0.003 mg/kg/day where it effected inflammation of the prostrate of male rats fed RDX for 2 years (McLellan, Hartley, and Brower 1988a).

HMX

HMX (Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine) is a code name for High Melting Explosive. This explosive is described as a colorless crystalline solid with about 1.3 times the explosive power of TNT (Sullivan et al. 1979). HMX has been used as a component in plastic-bonded explosives, solid-fuel rocket propellants, and military munitions (Sullivan et al. 1979; Kitchens Brownlee 1979). The production of HMX involves the nitration of hexamine with ammonium nitrate and nitric acid in an acetic acid/acetic anhydride solvent. HMX has a low-water solubility (6.63 mg/ℓ at 20 °C). Other properties of HMX are listed in Appendix A.

HMX is classified as an EPA Group D compound: not classified as a Human Carcinogen (McLellan, Hartley, and Brower 1988b). The USEPA's lifetime health advisory for HMX is set at 0.4 mg/ℓ (400 ppb) for adults and was determined based on a DEWL of 2.0 mg/ℓ. The DWEL is based on an

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RfD of 0.05 mg/ kg/day where the effect was the absence of liver lesions in male rats fed HMX for 13 weeks.

Well 410

Well 410, as previously discussed, is reported as the most contaminated well. For this reason, this study focuses on its treatment. In particular, this study examines the treatment of RDX from Well 410 because the concentration of HMX measured in samples collected are below the health advisory limit.

Well 410 was installed in 1942. This well is 85 ft deep and is screened from 75 to 85 ft below ground surface. It is a 10-in. diam well capable of delivering from 300 to 320 gal per minute of water (U.S. Geological Survey (USGS) 1991; Dames and Moore 1991).

Well 410 is located in Site 138 approximately 300 ft to the north of Building 407 (Figure 4). It draws water from a confined aquifer in the stratified drift aquifer system. This aquifer has three permeable layers: A3, which is unconfined, and two confined layers, A4 and A5 (Figure 5). A4 and A5 are separated by low permeability layers, C3 and C4.

The USGS (1991) reports that the groundwater horizonal flow gradient in the confined aquifer (A5) under unstressed conditions is predominantly down-valley (south) as shown on the potentiometric surface map (Figure 6). Groundwater modeling efforts were conducted by the USGS. Figure 7 shows the model prediction of selected vertical flow paths under nonpumping conditions. Figures 8 and 9 show computed flow paths of the groundwater at the same location but with the drinking water-supply Well 410 continuously pumped at 350 gpm.

The model predicts that groundwater recharge from the area around Picatinny Lake supplies groundwater to Well 410. In addition, this model predicts the significant vertical leakage from the lower part of permeable layer A3 through layers C4 and C5 to aquifer A5.

In summary, the water pumped from Well 410 entered the groundwater system in the vicinity and directly from Picatinny Lake, and its travel time is estimated to be less than 5 years. In the absence of pumping, this water would have continued down-valley and discharged to Green Pond Brook.

Water-Supply Treatment Facility

Water is pumped from Wells 410 and 430A to the water-supply treatment facility (WSTF), Building 1383. Prior to entering the primary surge tank located at Building 1383, water from Well 129 is combined with the water
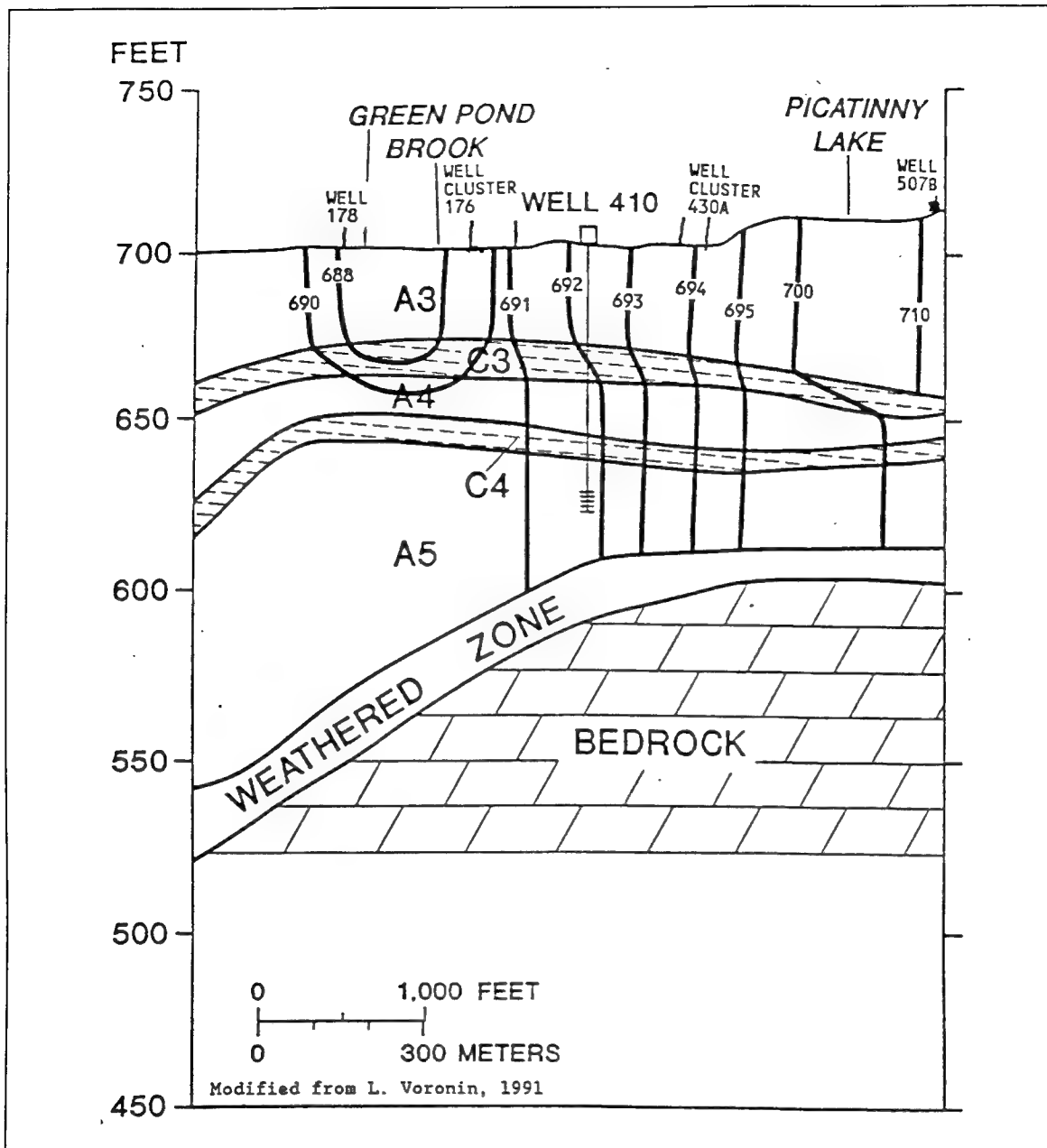
Figure 5. Hydrogeologic section in vicinity of Well 410 showing head data measured April 1989 (source: USGS 1991)

from Wells 410 and 430A. Each well (410, 430A, and 129) has an approximate capacity of 300 gpm. The WSTF consists of four main treatment processes: chemical addition and filtration, air stripping, pH control treatment, and chlorine addition. A process diagram of the WSTF is shown in Figure 10. Details of the WSTF are described as follows.

Untreated water enters the WSTF and is briefly stored in the primary surge tank. The water contained in the primary surge tank is pumped through three
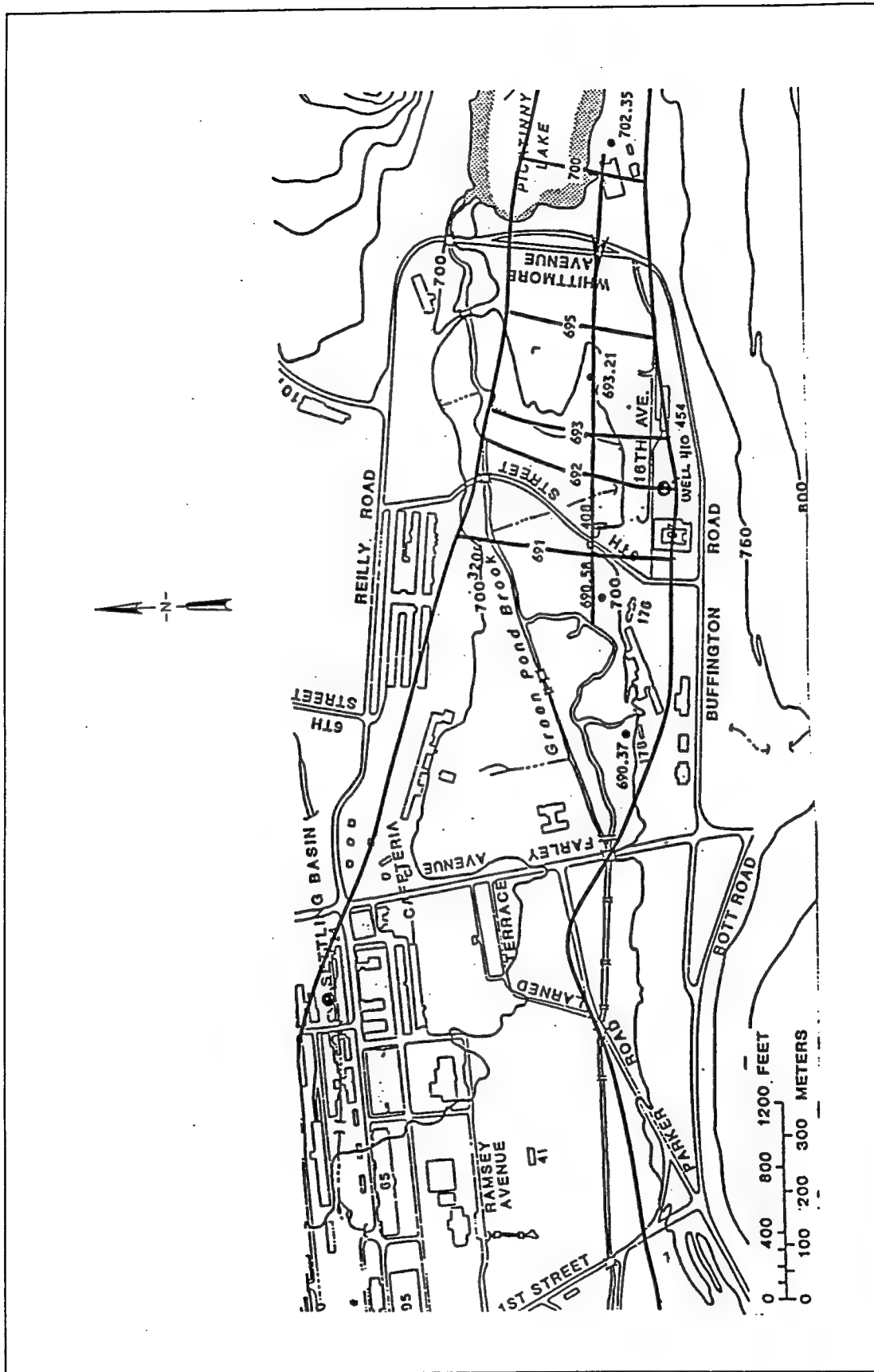
Figure 6.   Potentiometric surface in permeable layer A5 and groundwater flow in area of Well 410, April 1989 (source: USGS 1991)
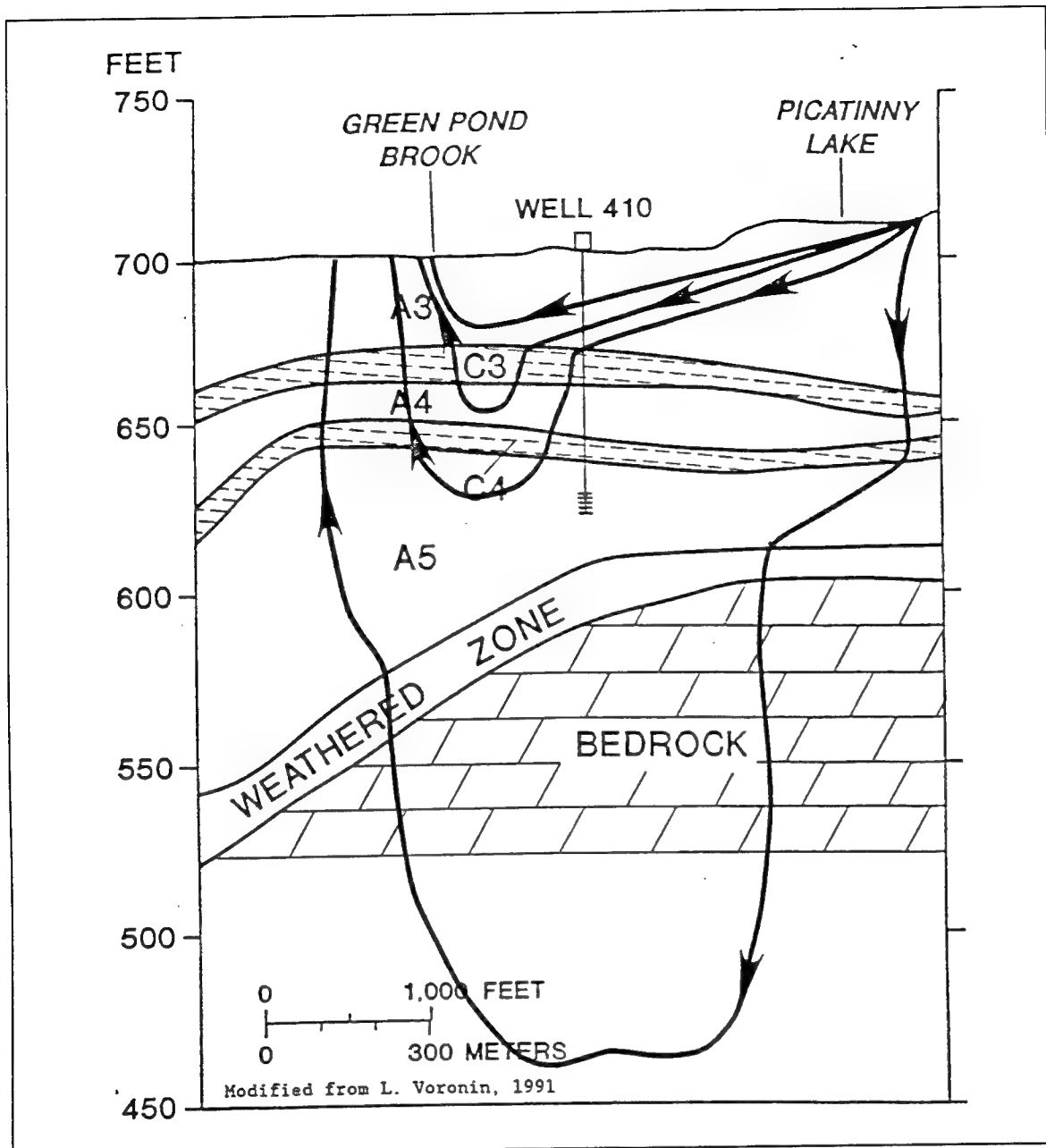
Figure 7.   Hydrogeologic section showing groundwater flow paths under steady-state non-pumping conditions in area of Well 410 (source: USGS 1991)

raw water pumps operated in parallel. Soda Ash and potassium permanganate are added (in-line) to the water from the raw water pumps and then enter three green sand pressure filters plumbed in parallel for the removal of iron and manganese. After filtration, water flows to an air stripper column where volatile organic contaminants (primarily TCE) are removed using a counter current air flow. The stripped water enters a settling tank where any oxidized iron or particulate are removed. The water then overflows a weir and enters a secondary surge tank. From the secondary surge tank, the water is pumped
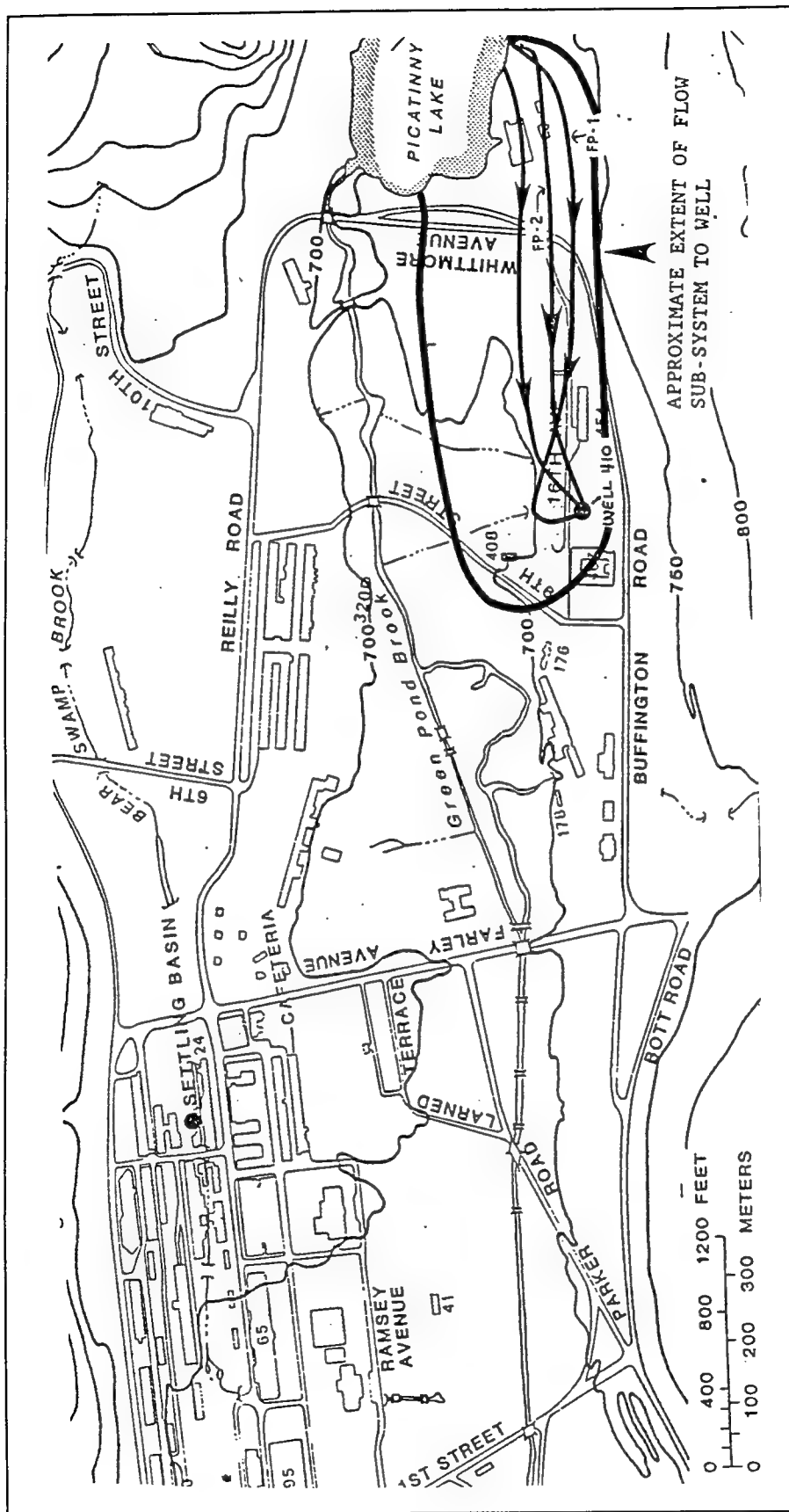
Figure 8. Map view of groundwater flow paths around Well 410 with well pumping (source: USGS 1991)
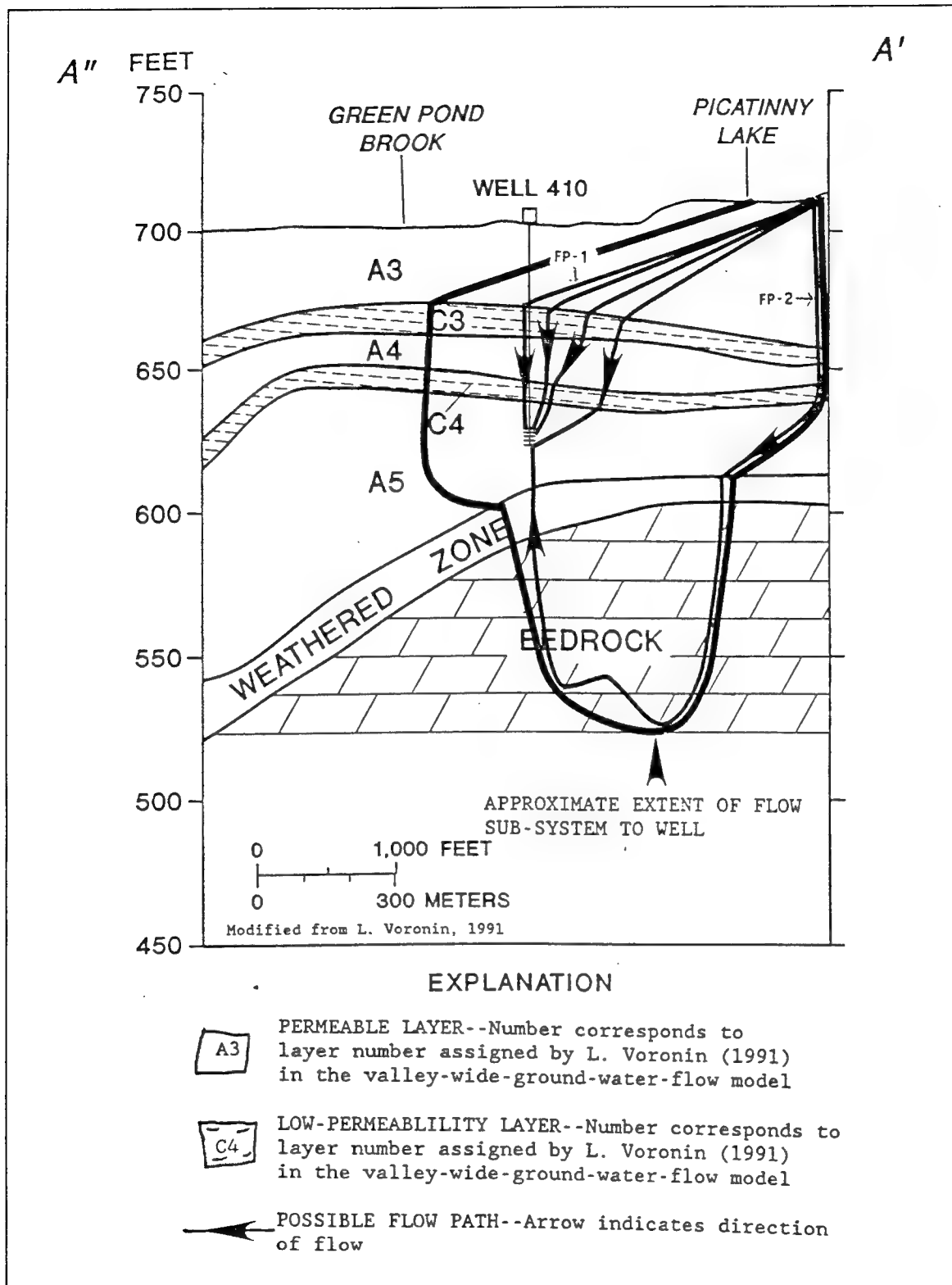
Figure 9.   Hydrogeologic section showing groundwater flow paths under pumping conditions in area of Well 410 (source: USGS 1991)
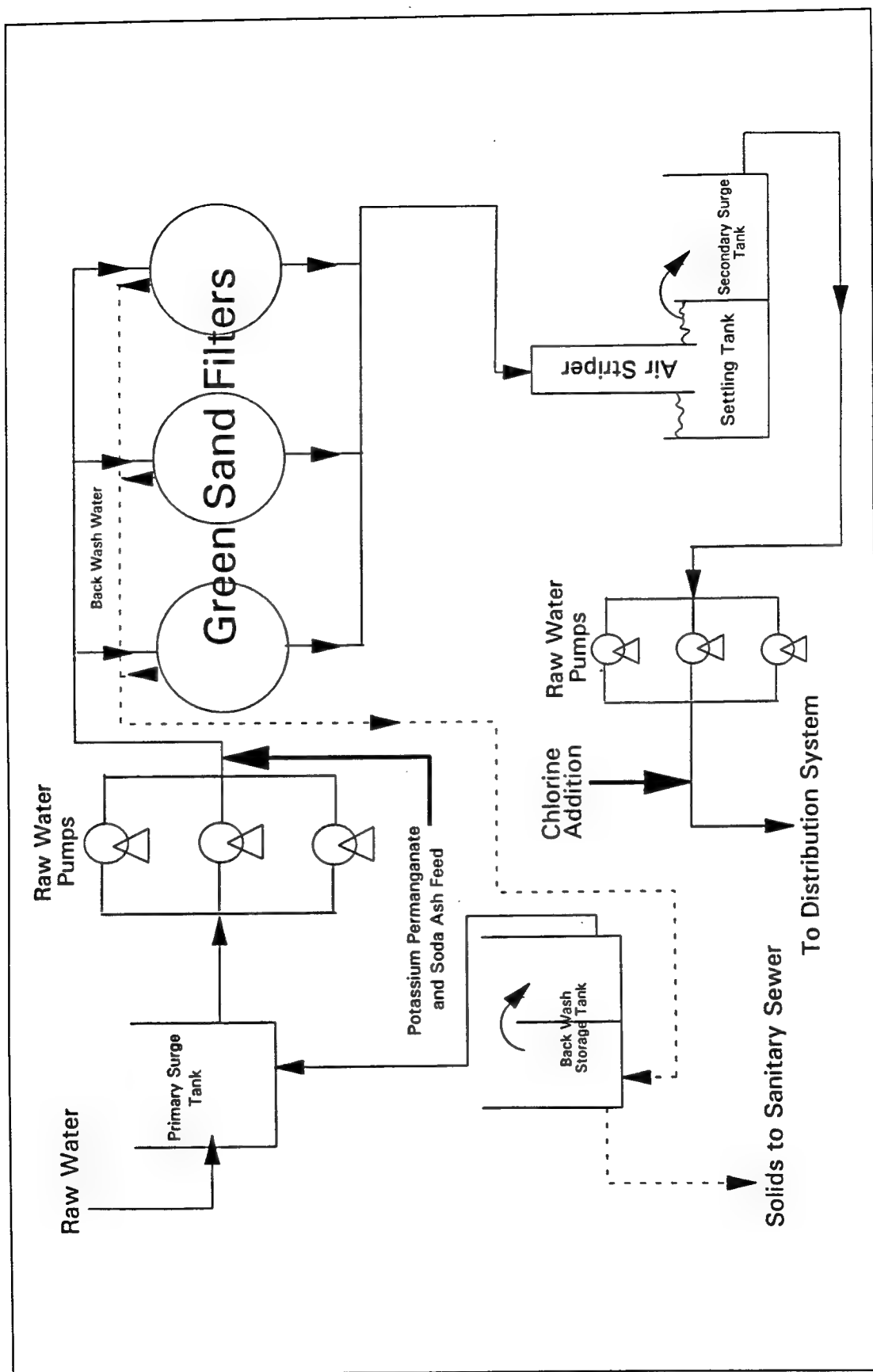
Figure 10. Water-supply treatment facility

through three treated water pumps plumbed in parallel, and chemicals are added for pH control. Chlorine is added in-line to the water from the pumps and then enters the distribution at PTA.

Granular Activated Carbon Treatment

In a report prepared for USATHAMA by Roy F. Weston, Inc. (Wujcik, LoMw, and Marks 1989), five technologies are reported to be effective for the removal of explosives from aqueous streams. These include the following:

a. Granular activated carbon treatment.

b. Polymeric adsorption resins treatment.

c. Ultraviolet (UV) light with ozonation and/or hydrogen peroxide treatment.

d. Chlorine oxidation treatment.

e. Activated sludge biological treatment.

Currently, the most utilized technology for the treatment of RDX-contaminated waters is granular activated carbon (GAC). This report will focus on the removal of RDX using GAC.

Granular activated carbon

Production. Activated carbon is found in two forms: powdered and granular. Powdered activated carbon is defined as the activated carbon material that passes a No. 50 sieve, and GAC is retained by the No. 50 sieve (Chermisinoff and Ellerbusch 1978). GAC can be generated from almost any material that has a high carbon content. Typical substrates used for the production of activated carbon are listed in Table 3 (Cheremisinoff and Ellerbush

| Table 3 |
Source Materials for Activated Carbon
Bituminous Coal
Bones
Coconut Shells
Lignite
Peat
Pecan Shells
Petroleum-Based Residues
Paper Mill Black-Ash
Sugar
Wastewater Treatment Sludges
Wood

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1978). These substrates are converted to activated carbon using a two-step process involving carbonization and activation.

Carbonization involves removing the majority of the water from the substrate, converting the organic matter to elemental carbon, and driving off the noncarbon portion of the substrate. Carbonization is accomplished by slowly heating the substrate under reducing conditions to temperatures ranging from 400 to 600 °C (Cheremisinoff and Ellerbusch 1978; Kipling 1956).

Activation is an oxidation process where the carbonized material is exposed to an oxidizing gas (i.e., steam, air, carbon dioxide, chlorine, or sulphur vapor) at elevated temperatures. The oxidizing agent and the temperature of activation are critical to the sorptive properties of the carbon (Wolf 1958; Kipling 1956). Small quantities of ash in the activated carbon reduces the carbon sorptive properties. Ash is produced from nonoxidized material that can be introduced by the oxidizing agent.

Properties of activated carbon. Activated carbon's basic structural unit is closely approximated by the structure of pure graphite (Cheremisinoff and Ellerbusch 1978). This idealized structure was first introduced by Benal as a stable hexagonal lattice as shown in Figure 11 (Walker 1962). The structure is composed of a system of infinite layers of fused hexagons. While the idealized structure of carbon is helpful in visualizing the molecular orientation of the carbon structure, most carbons of commercial interest deviate from this idealized structure. These deviations generally manifest themselves as stacking disorders between the layered planes in the carbon structure (Walker
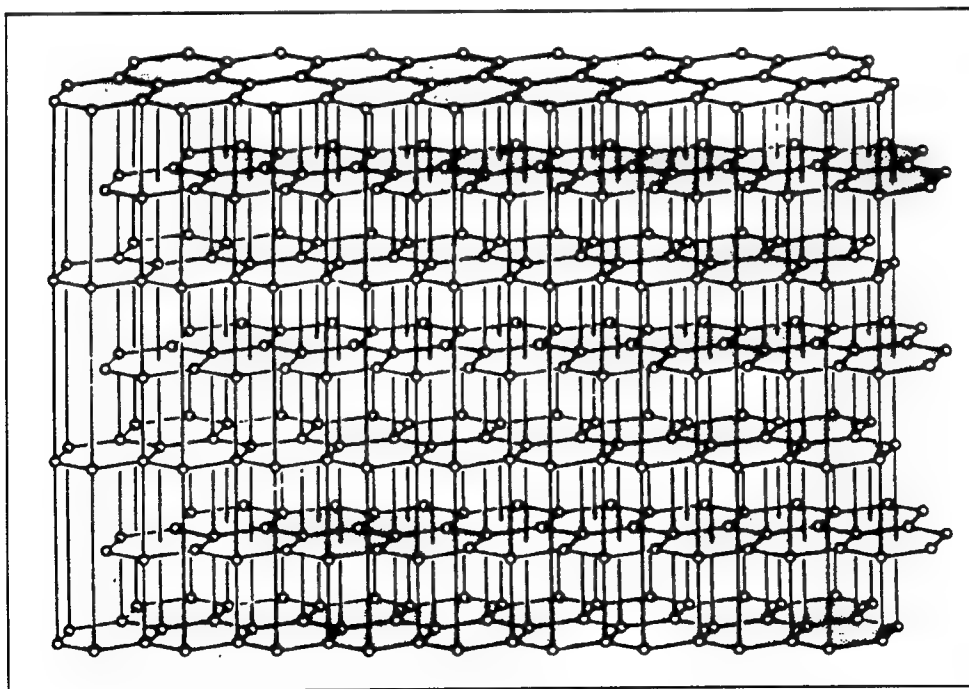
Figure 11. Idealized structure of activated carbon (source: Foust and Aly 1987)

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1962). This stacking disorder is termed "turbostratic" and is illustrated in Figure 12. The literature indicates that impurities in the raw materials (substrate) used in the production of carbon are responsible for this stacking disorder. These impurities (or stacking disorders) are reported to influence the formation of interior vacancies (pores) in the microcrystalline structure (Walker 1962; Cheremisinoff and Ellerbusch 1978). These vacancies are responsible for a large portion of the activated carbon's sorptive capacity (Cheremisinoff and Ellerbusch 1978; Kipling 1956; Foust and Aly 1987).
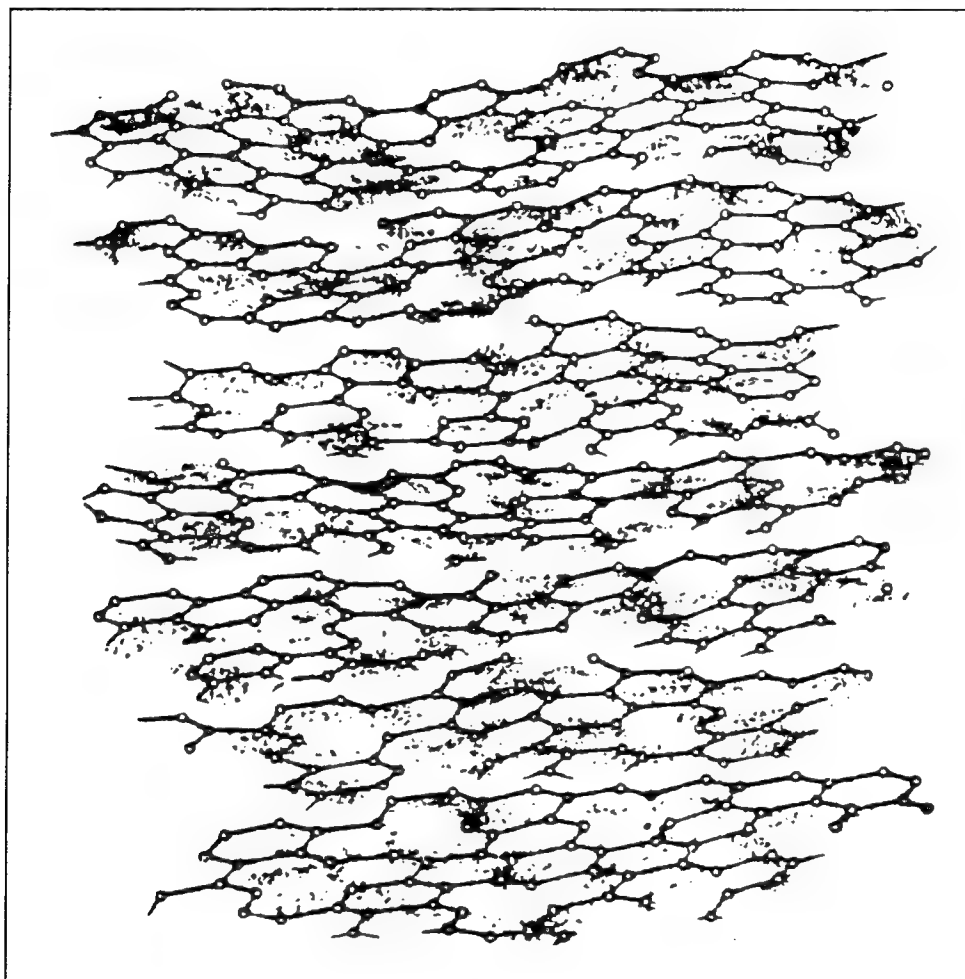
Figure 12. Nonidealized structure of activated carbon showing "turbo-stractic" details (source: Foust and Aly 1987)

A typical carbon particle is illustrated in Figure 13 (Foust and Aly 1987). Pores such as those depicted in Figure 13 give activated carbon its large surface area, which influences its sorptive characteristics. These pores are divided into two types: macropores and micropores. Macropores are large, generally greater than 1,000 angstroms. Micropores are small and range in size between 10 and 1,000 angstroms. These micropores result from the formation of microcrystalline vacancies. Macropores do not add appreciably to the surface area of the carbon particle but provide a passageway for

22
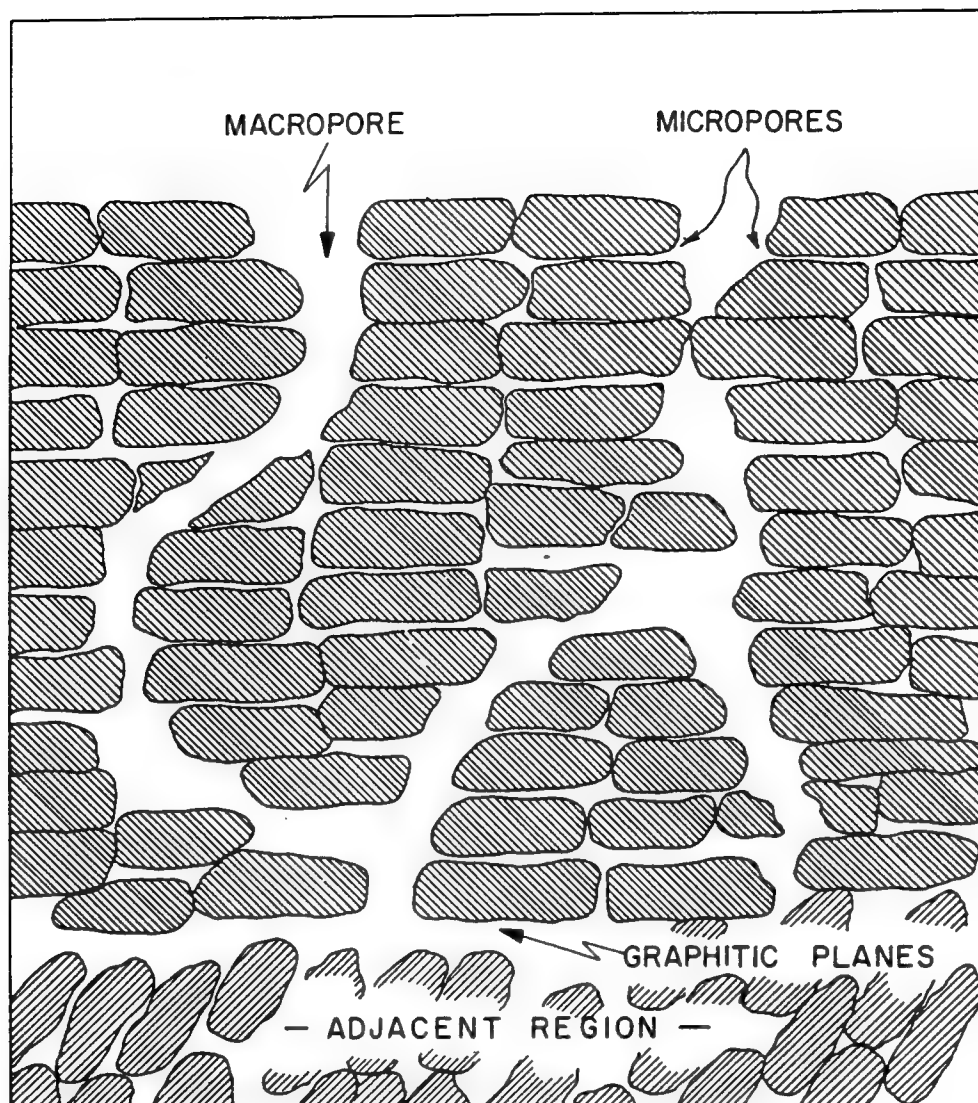
Figure 13. Diagram of a carbon particle depicting its porous nature (source: Foust and Aly 1987)

material to diffuse to the interior of the carbon particle. The micropores contribute the majority of the carbon particles surface area.

Surface area is critical to the sorption characteristics of activated carbon. In general, the larger the surface area the higher the sorption capacity of activated carbon. Consequently, large (adsorbate) molecules that block off micropores effectively reduce the particle's surface area. Thus, as depicted in Figure 14, carbon sorption is a process highly dependent on the molecular size of the adsorbate (dissolved phase) and the physical characteristics of the activated carbon (Cheremisinoff and Ellerbusch 1978).

As discussed above, the properties of the activated carbons will vary depending on the substrate used to produce the activated carbon. In general,
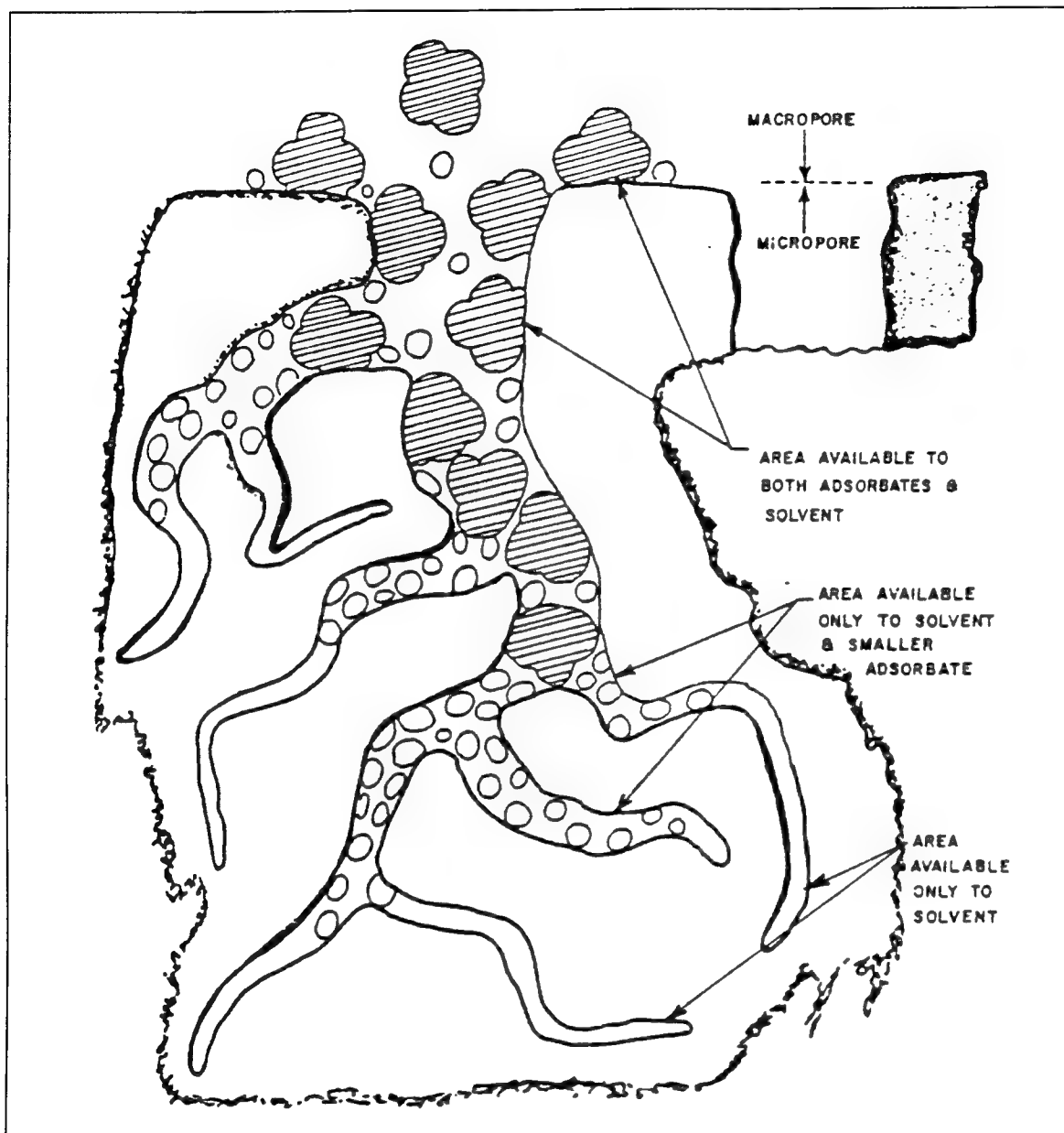
Figure 14. Diffusion of contaminants into pore structure of a carbon particle (source: Cheremisinoff and Ellerbusch 1978)

GAC produced from bituminous coal has a small pore size, a large surface area, and the highest bulk density. Carbon produced from lignite coal has the largest pore size, least surface area, and lowest bulk density (Eckenfelder 1989).

Several tests have been developed to characterize the sorptive properties of carbon. These include the phenol number, iodine number, molasses number, and the abrasion number. Specifics of these numbers are listed below (Eckenfelder 1989).

a. Phenol number. Relates to the ability of activated carbon to adsorb taste and odor-causing compounds. High numbers are more effective for taste and odor.

b. Iodine number. Relates to the ability of activated carbon to adsorb low-molecular-weight adsorbates. High numbers are more effective for low-molecular-weight adsorbates.

c. Molasses number. Relates to the ability of activated carbon to adsorb high-molecular-weight adsorbates. High numbers are more effective for high-molecular-weight adsorbates.

d. Abrasion number. Relates to the ability of activated carbon to resist the physical effects of abrasive forces and to remain intact. High numbers indicate that the carbons are more abrasive.

Sorption theory

Three terms are generally used when discussing activated carbon: adsorption, absorption, and sorption. Adsorption generally refers to the physical adhesion of molecules or particles to the carbon surface without a chemical reaction. Absorption involves the penetration of the molecules or particles into the carbon surface. Sorption is used to refer to both processes (adsorption and absorption) which generally occur simultaneously (Wentz 1989).

Sorption involves the movement of a contaminant from the bulk of the liquid to the carbon surface. As sorption proceeds, the sorbed solute tends to desorb back into solution. Over time, equal amounts of solute are sorbed and desorbed simultaneously. When this occurs, the system is said to be at equilibrium (or steady state). Conditions of the system such as solute, adsorbent, solvent, temperature, and pH affect equilibrium (Foust and Aly 1987).

Generally, GAC laboratory investigations consist of equilibrium tests and continuous flow carbon tests. Equilibrium tests typically are conducted at constant temperature and thus are referred to as sorption isotherm tests. Typically, adsorbed quantities increase with an increase in the solute concentration as illustrated by the adsorption isotherm in Figure 15. The shape of the isotherm curve provides important information regarding the sorption process. Isotherm curves can provide qualitative information about the adsorption process and the extent of the surface coverage by the adsorbate. Carbon isotherm for wastewater treatment typically exhibits the shape shown in Figure 15. It was reported by Foust and Aly (1987) that isotherms having this shape exhibit monomolecular layer adsorption although under certain conditions multilayer adsorption may be observed. Isotherm curves of this shape are characterized by two phases of sorption. The first portion of the curve (from A to B in Figure 15) is the linear portion of the sorption curve. In this portion of the curve, as concentration of the liquid increases, the solid phase capacity for the contaminant increases linearly. The steeper the linear portion of the curve the
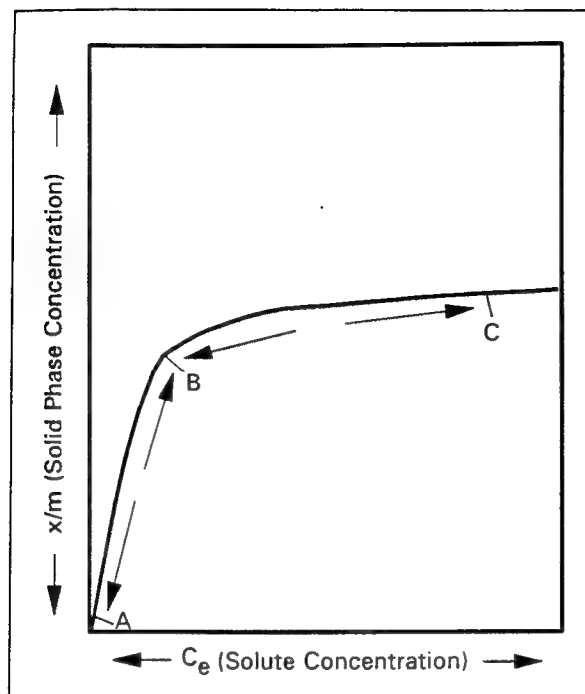
Figure 15. Typical carbon adsorption isotherm

higher the affinity of the contaminant for carbon. In the second phase of the curve (from B to C in Figure 15), the carbon asymptotically approaches its ultimate sorbative capacity for the contaminant. Higher ultimate capacities are indicative of carbon that can be loaded with large amounts of contaminant.

Isotherm curves provide a quick method for comparing the effectiveness of different activated carbons for various contaminants. This is generally recommended as the first step in assessing the feasibility of GAC (Rizzo and Shepherd 1977; Calgon Corporation 1988; Foust and Aly 1987). Typically, carbon isotherms are modeled using Langmuir's or Freundlich's model.

Langmuir model. The Langmuir equation was originally derived based on basic kinetic consideration and utilizes the following assumptions:

a. The molecules are adsorbed on definite sites on the surface of the adsorbent.

b. Each site can accommodate only one molecule.

c. The area of each site is a fixed quantity determined solely by the geometry of the surface.

d. The adsorption energy is the same at all sites.

Using these assumptions, Langmuir expressed this equation as (Foust and Aly 1987):

$$X = \frac{X_m b C_e}{1 + b C_e} \tag{1}$$

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where

X = x/m (the solid phase concentration) = qe

x = amount of solute adsorbed

m = weight of adsorbent

X_m = amount of solute adsorbed per unit weight of adsorbent required for monolayer coverage of surface

b = a constant related to heat of adsorption

C_e = equilibrium concentration of solute

Rearranging Equation 1 provides the linear equation shown in Equation 2

$$\frac{C_e}{X} = \frac{1}{bX_m} + \frac{C_e}{X_m} \tag{2}$$

When C_e/X is plotted against C_e, a straight line, having an intercept $1/bX_m$ and a slope $1/X_m$, is obtained. Thus, X_m and b can be determined experimentally from this plot.

Freundlich model. Unlike the Langmuir model, which is based on theory, the Freundlich model is based on an empirical expression. The Freundlich equation is expressed as (Weber 1972):

$$\frac{x}{M} = KC_e^{\frac{1}{n}} \tag{3}$$

where

x = amount of solute adsorbed

M = weight of adsorbent

C_e = solute equilibrium concentration

K and $1/n$ = constants characteristic of system

The linear form of this equation can be written as:

$$\log \frac{x}{M} = \log K + \frac{1}{n}\log C_e \tag{4}$$

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Plotting $\log x/M$ versus $\log C_e$, a straight line is obtained with a slope of $1/n$, and $\log K$ is the intercept. Thus, n and K can be determined experimentally from this plot.

By comparing n and K or X_m and b for various carbons, determinations regarding the relative sorption effectiveness of the carbons can be made.

Dynamic column testing

Although equilibrium isotherm testing is very useful for determining the feasibility of GAC for the removal of the contaminants and comparing the effectiveness of different carbons, dynamic column testing must be performed to determine the optimum contact time and the rate at which the contaminant is adsorbed by the carbon (Rizzo and Shepherd 1977). Additional information that can be obtained from dynamic column testing includes (Edwards 1988; Calgon Corporation 1988; Eckenfelder 1989):

a. A basis for final carbon selection.

b. A determination of whether the GAC will meet effluent standards.

c. A basis for estimating full-scale system costs.

d. The determination of biological activity that may affect the operation of the carbon system and the apparent carbon capacity for the contaminant.

Generally, it is recommended for GAC pilot testing that 15 linear feet of carbon be used in a minimum of four individual columns. Columns should be at least 1.5 in. in diameter because with smaller columns, wall effects become significant. Generally 4-in. columns are used and operated in either up-flow or down-flow mode. Contact times range from 15 to 60 min or greater, and a typical hydraulic loading is 1 to 3 gal/square foot (Calgon Corporation 1988; American Norit Company, Inc. 1987; Rizzo and Shepherd 1977; and Edwards 1988).

As the pilot test is conducted, water is pumped through the column system and effluent samples are collected at appropriate time intervals. The point where the adsorbate is detected in the effluent above the effluent criteria is termed breakpoint. As the system is operated, the concentration of the effluent will approach that of the influent. A plot of the volume of water that has passed through the columns versus the effluent concentration can be plotted. This is termed the breakthrough curve (Figure 16). During the adsorption cycle in the column, a portion of the inlet section of the carbon bed will become saturated with contaminant. At the same point in time, the carbon near the top of the column will be only partially loaded with adsorbate. The extent of saturation will depend on the system design and operating parameters. The area between these two extremes is a zone where sorption is

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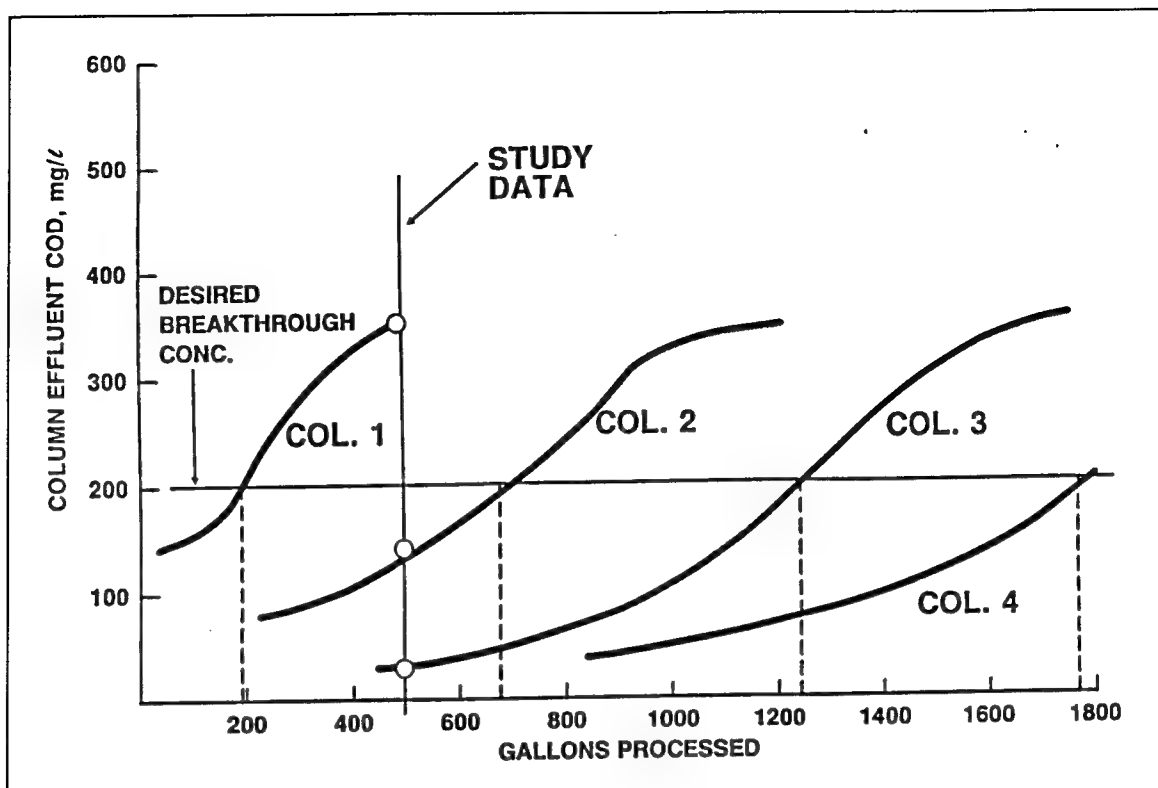
Figure 16. Example of typical data from a four-column breakthrough study. Modified column data also presented as "study data"

occurring. This zone is called the mass transfer zone (MTZ). As more water is pumped through the column, the MTZ will move through the column as shown in Figure 17.

The MTZ is driven by the kinetic sorption effects. Contaminants that are quickly adsorbed will have small MTZ, while contaminants slowly adsorbed will have a wide MTZ. The width of the MTZ is determined by the equilibrium sorption. In systems that exhibit small MTZ, column height in a full scale operation is less critical than a system with a large MTZ. Systems with large MTZ will benefit from longer columns (Foust and Aly 1987).

Carbon Selection

There is a relatively large number of supply sources for activated carbon. In fact, over 43 are discussed by Hinshaw et al. (1987). For this study, it was determined that five carbon types would be investigated. Review and evaluation of 43 carbon sources is beyond the scope and resources of this study. To narrow the carbons from over 43 types to 5 types required a logical selection process. The process used for this study is discussed as follows.
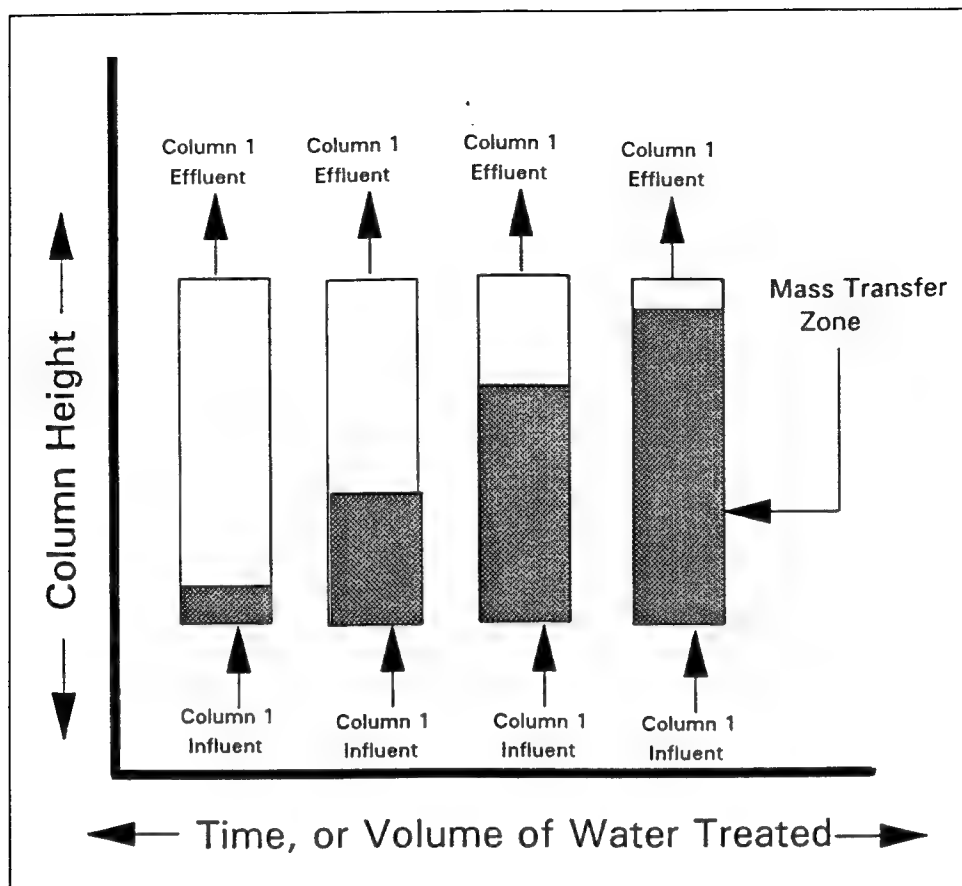
Figure 17. Schematic representation of movement of mass transfer zone
through a single column with increasing water volume (or time)

The first step in this selection process was to review what types of carbon
have proven to be effective for the treatment of military explosive compounds.
A detailed literature review uncovered three key reports that studied the
effects of military explosive compounds on carbon (Hinshaw et al. 1987;
Wujcik, LoMw, and Marks 1989; and Dennis et al. 1990). Hinshaw et al.
(1987) reports that "the majority, if not all, Army Ammunition Plants use
Calgon Filtrasorb 300 (F-300) GAC" for the treatment of explosive-processing
water (pink water). Hinshaw adds that it is reported that F-300 has a lower
adsorption capacity than Calgon Filtrasorb 200 (F-200), but F-200 should be
investigated as a replacement for F-300. The GAC investigated by these
investigators are listed below:

Manufacturer	Carbon Type	
Calgon	Filtrasorb	200
Calgon	Filtrasorb	300
Calgon	Filtrasorb	400
Westvaco	Nuchar	WV-G
Witco	Witcarb	950
American Norit	Hydrodarco	3000

Not all of these carbon types were utilized in each investigation. The first three carbons listed were studied in each investigation. Westvaco and Witco carbons were evaluated by two of the investigations, and the American Norit carbons were only studied by a single investigation.

The second selection criteria utilized was to investigate carbons that had a wide range of properties and costs and were prepared from various substrates. Based on the data provided by the manufacturers of the various carbons, the five carbons listed in Table 4 were chosen for investigation in this study. The properties of these carbons are listed in Table 5. In addition to the properties listed in Table 5, copies of the manufacturers product bulletins for each of these carbons are presented in Appendix B.

Table 4
Carbon Types Evaluated in This Study

Manufacturer	Carbon Type	Abbreviation
Westates Carbon, Inc.	CC-601	CC-601
Calgon Carbon Corp.	Filtrasorb 200	F-200
Calgon Carbon Corp.	Filtrasorb 400	F-400
American Norit Co.	Norit ROW 0.8	ROW 0.8
American Norit Co.	Hydrodarco 4000	H-4000

Table 5
Properties of Carbon Types Evaluated in This Study

Property	F-400	F-200	ROW 0.8	H-4,000	CC601
Substrate Material	Bituminous Coal	Bituminous Coal	Extruded Coal	Lignite Coal	Coconut Shell
Iodine number	1,000	850	1,000	600	1,100
Abrasion number	75	75	92	80	99
Surface area, m^2/g	900-1,100	850-900	N/A	625	N/A
Bulk density, lb/ft^2	27	29	24.8	24	30.5
Pore volume, cc/g	0.85-0.95	N/A	1.0	0.93	N/A

Note: N/A = Not available.

Historical Treatment of Explosives-Contaminated Groundwater

Generally, the main concern for the treatment of HMX and RDX was associated with solid waste or wastewater from processing and manufacturing facilities. Much of the currently available literature involves the use of GAC

for the treatment of explosive-contaminated wastewater (pink water) rather than the treatment of groundwater (Wujcik, LoMw, and Marks 1989). GAC is the primary treatment used for these wastes and has been known to be effective in removing HMX and RDX to limits that permit discharge.

An isotherm study conducted by Hinshaw (Hinshaw et al. 1987) investigated the treatment of synthetic and actual "pink water" at HMX and RDX concentration levels around 5 and 27 ppm, respectively. At carbon dosages of around 10 mg/ℓ, this study indicated little or no removal of the contaminants. In fact, substantial treatment did not occur until the carbon dosage exceeded 1,000 mg/ℓ. Isotherm data for this study are presented in Tables 6 and 7, and the RDX and HMX isotherm curves are shown in Figures 18 and 19. In addition, the data from this study indicated that as the carbon dosage was increased, the removal efficiency of HMX and RDX increased as shown in Figure 20.

Table 6
Isotherm Test Results Using a Synthetic Pink Water and Calgon Filtrasorb 200 (Source: Hinshaw et al. 1987)

Carbon Dosage mg/ℓ	RDX Equilibrium Conc. (C_e) mg/ℓ	RDX Carbon Conc. (q_e) mg/g	HMX Equilibrium Conc. (C_e) mg/ℓ	HMX Carbon Conc. mg/g
0	27.7	N/A	5.71	N/A
9.2	27.6	0.0109	5.61	0.0109
50.2	22.9	0.0957	4.06	0.0329
203	15.9	0.0582	1.91	0.01897
1,001	0.0990	0.0276	0.00412	0.0057
4,997	0.00400	0.0055	ND	N/A

Note: N/A = Not applicable; ND = Not detected.

Table 7
Isotherm Test Results Using a Synthetic Pink Water and Calgon Filtrasorb 400 (Source: Hinshaw et al. 1987)

Carbon Dosage mg/ℓ	RDX Equilibrium Conc. (C_e) mg/ℓ	RDX Carbon Conc. (q_e) mg/g	HMX Equilibrium Conc. (C_e) mg/ℓ	HMX Carbon Conc. (q_e) mg/g
0	23.7	N/A	4.45	N/A
12.8	23.3	0.0312	4.35	0.0078
52.7	21.6	0.0398	3.70	0.0142
203	7.29	0.0810	0.402	0.0200
997	0.0521	0.0237	0.00270	0.0045
5,001	0.00528	0.0047	<MDL	N/A

Note: N/A = Not applicable; ND = Not detected; MDL = Minimum detection level.

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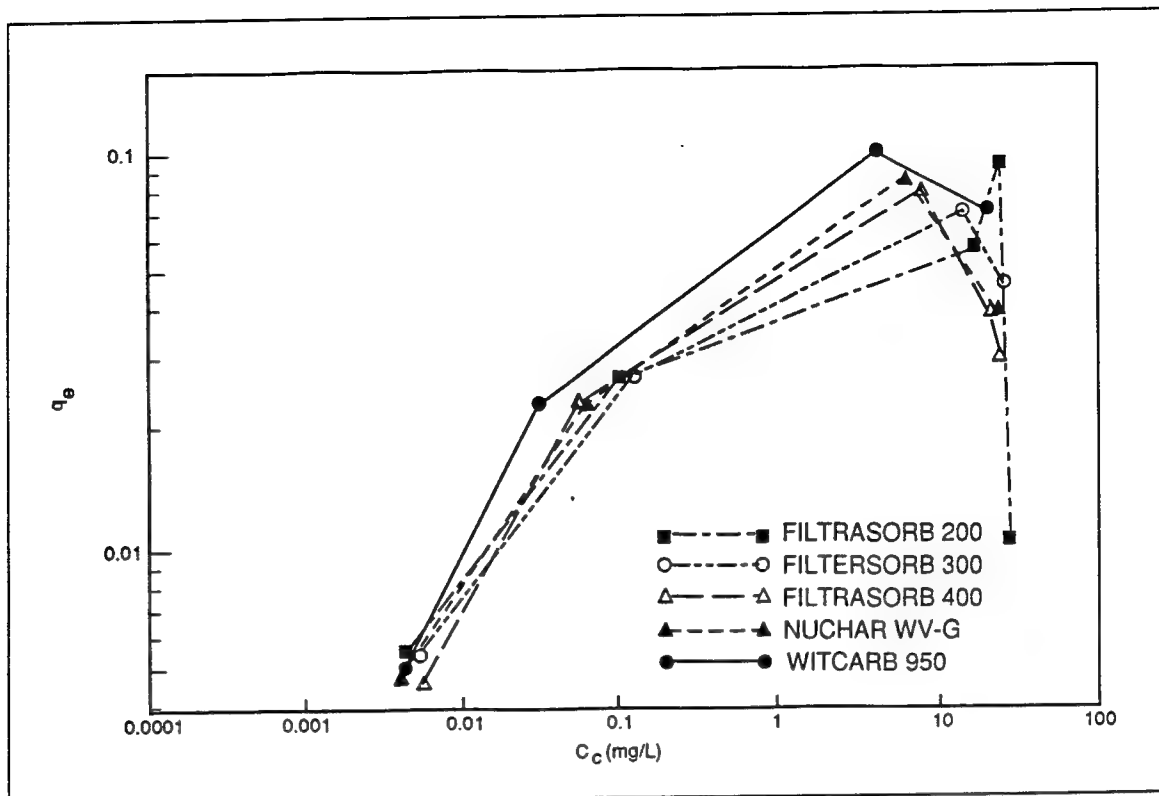
Figure 18. RDX isotherms for five granular activated carbons and a synthetic pink water having an initial concentration of 27.7 ppm (source: Hinshaw et al. 1987)

Another study conducted by Roy F. Weston, Inc. (Dennis et al. 1990) investigated the use of GAC to treat RDX- and TNT-contaminated groundwater from Milan Army Ammunition Plant (MAAP) using isotherm tests. The groundwater contained RDX concentrations in excess of 486 ppb and HMX concentrations of 2.75 ppb. Isotherm tests indicated only about 50-percent removal of the RDX at carbon dosage levels of 10 mg/ℓ. Effective treatment was not achieved until the wastewater was dosed with carbon concentrations in excess of 200 mg/ℓ. At this dosage (200 mg/ℓ), the RDX concentration in the treated effluent was in excess of 3 ppb. HMX, on the other hand, was completely removed below the detection limit (1.30 ppb) at even the lowest carbon dosage of 10 mg/ℓ.

Wujcik, LoMw, and Marks (1989) reports on the removal of 2,4-dinitrotoluene (2,4-DNT) and 2,6-dinitrotoluene (2,6-DNT) from contaminated groundwater at Badger Army Ammunition Plant. In this study, the groundwater was contaminated with approximate concentrations of 1 and 0.6 ppm 2,4-DNT and 2,6-DNT, respectively. Isotherm testing with GAC indicated that carbon dosages in excess of 5,000 mg/ℓ were required to reduce the carbon concentration levels to less than 0.6 and 0.5 ppb 2,4-DNT and 2,6-DNT, respectively.
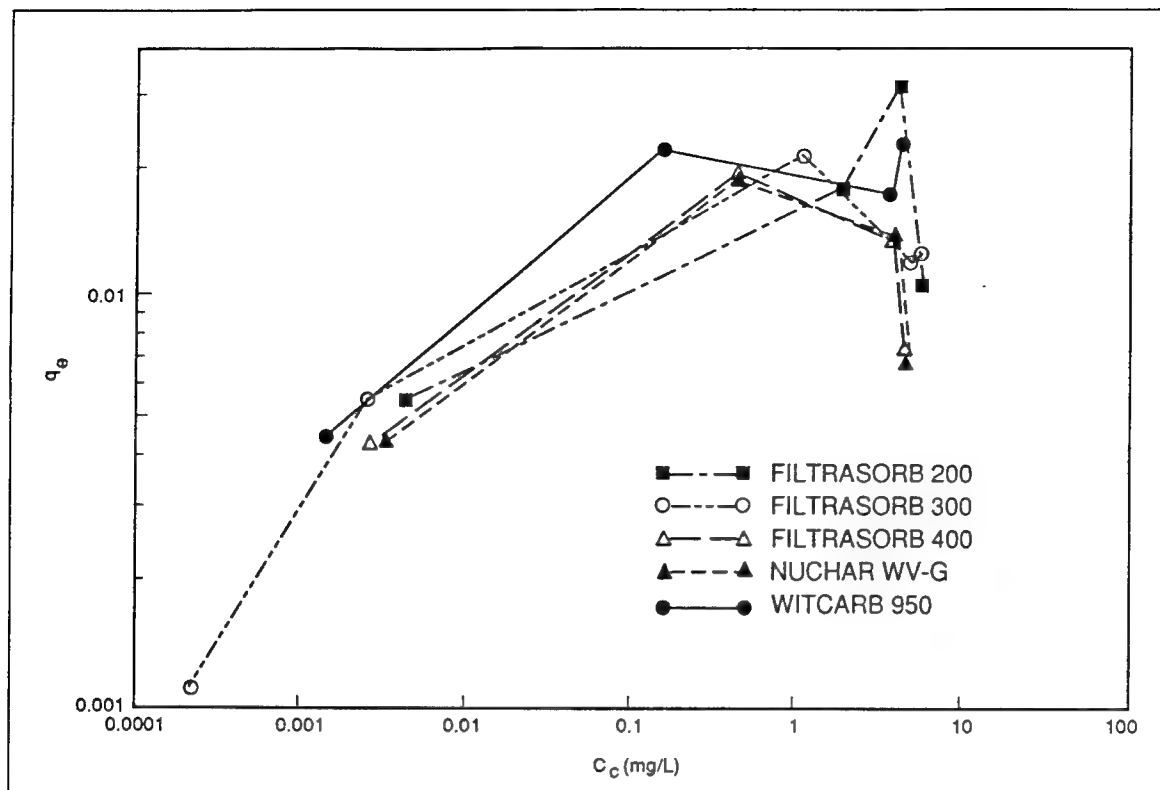
Figure 19. HMX isotherms for five granular activated carbons and a synthetic pink water having an initial concentration of 5.76 ppm (source: Hinshaw et al. 1987)

No studies could be found on removing explosives from groundwater (or wastewater) that contained low levels (< 10 ppb) of explosive contaminant. Foust and Aly (1987) reported that "adsorbed quantities at equilibrium usually increase with an increase in the solute concentration." Based on this information and the information from the more concentrated explosive wastewater and groundwater studies, it was decided that carbon dosages that were higher than those used in these studies would be appropriate for this investigation.

Objective of Study

The main objective of this investigation was to determine the feasibility of using two technologies (granular activated carbon and UV/oxidation) in removing RDX and HMX from the drinking water at Picatinny Arsenal. While HMX was not considered as a controlling parameter in this investigation, HMX analysis was conducted concurrently with all RDX analysis.

GAC and UV/oxidation technologies were compared, and the recommendation of the most cost-effective technology is presented. This report only covers the presentation of GAC study and a cost comparison of the GAC and

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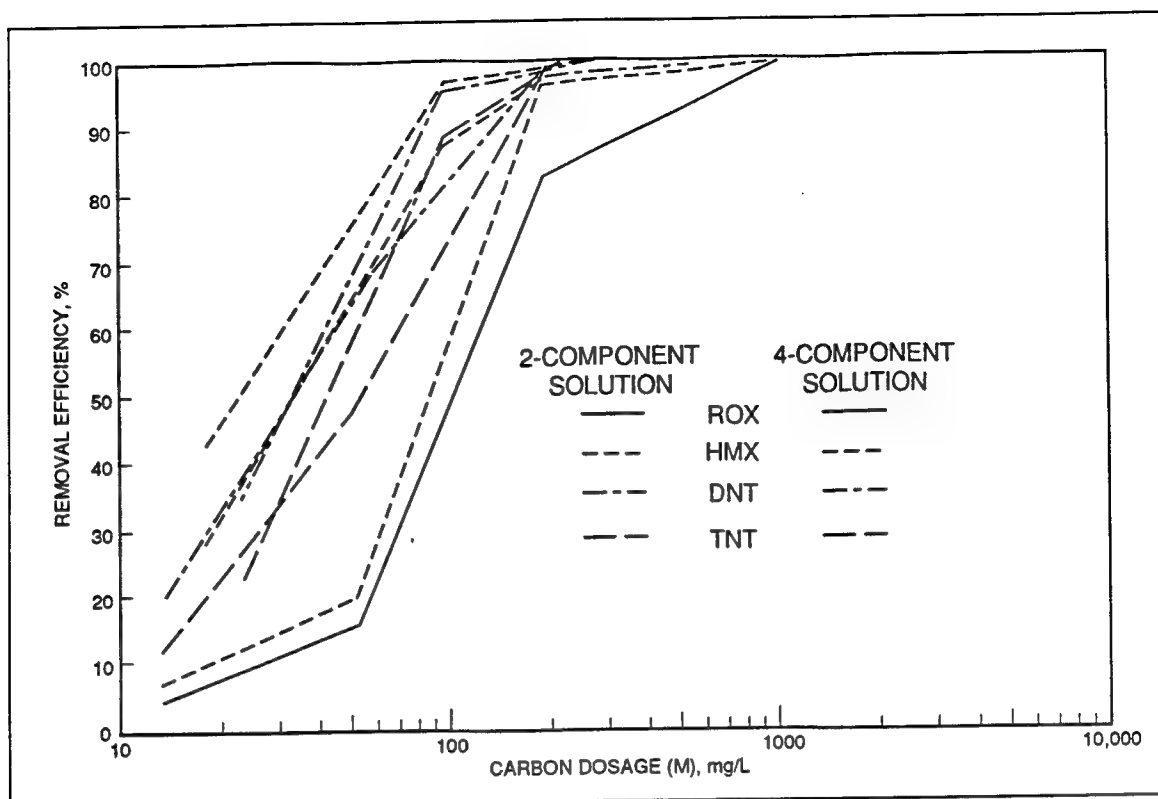
Figure 20. Nitro-compound removal efficiencies as a function of carbon dosage (source: Hinshaw et al. 1987)

UV/oxidation treatment system. The details of the UV/oxidation study are presented in a separate report (Fleming, Bricka, and Bailey 1995).

The goal of the GAC study was accomplished through a combination of laboratory bench (isotherm) tests and continuous flow pilot column tests. The treatability goal of this study was to remove the RDX to levels less than 1.0 ppb. The primary objectives of the isotherm studies were as follows:

a. Determine carbon capacities and associated exhaustion rates.

b. Develop relative rankings of GACs specific to the removal of RDX.

c. Estimate the capability of the GACs to meet the required water quality criteria for RDX.

d. Provide sufficient data to enable selection of two GACs to carry forward to pilot column testing.

The primary objectives of the pilot tests were as follows:

a. To determine the effectiveness of GAC to remove RDX from groundwater.

b. To determine adsorption capacities of the carbons for RDX.

c. To select the best-performing carbon of the two GACs based on their relative rates of adsorption.

d. To determine the optimal empty-bed contact time (EBCT) for GAC.

e. To provide design, operation, and cost information for a full-scale treatment scenario.

Project Approach

The GAC bench and pilot evaluation involved the following:

a. Identifying GAC to be tested in this study.

b. Collecting contaminated water for bench-scale isotherm evaluations.

c. Conducting the isotherm evaluations.

d. Selecting two GACs for pilot column studies.

e. Conducting the pilot column studies.

f. Comparing GAC adsorption treatment efficiencies and costs to that of UV/oxidation for the treatment of RDX-contaminated drinking water.

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2   Materials and Methods

Isotherm Testing

Prior to the initiation of this study, a meeting was held with PTA water treatment personnel to determine the best location for collection of the water samples for this study. PTA water treatment personnel explained the details of the water collection system that supplied water to the plant and the operation of the WSTF (as described in the Introduction - Well 410 and the Water-Supply Treatment Facility section of this report).

In this meeting, the WSTF personnel explained that Well 410 contained the highest concentration of explosives, with RDX and HMX being the main explosive contaminants of concern. Typical levels of RDX and HMX ranged from 4 to 6 and 1 to 3 ppb, respectively. The other wells (430A and 129) are either free of explosive contamination or contaminated with only a small amount of explosives. WSTF personnel also explained that under typical operation scenarios, most of the water supplied for the WSTF was pumped from Wells 430A and 129. Thus, the water supplied to the WSTF contains very low levels of RDX and HMX. This is advantageous in providing high quality drinking water but was not the best water supply for this study.

As a result of the information exchanged in this meeting, PTA water treatment officials and the U.S. Army Engineer Waterways Experiment Station (WES) study team agreed that water containing the higher explosive levels should be utilized for this study. Thus, all carbon testing was conducted on water collected at the well head of Well 410.

Since RDX levels were close to the detection limit (the detection limit = 0.6 ppb), care was taken to ensure that the measurable levels of RDX and HMX found in the water would be subjected to isotherm testing. The equipment that was utilized for the isotherm testing was transported to Picatinny, and a temporary laboratory was established in Building 1383 (WSTF). To reduce sample degradation, sample exposure to all plastic materials was minimized, and all samples that were stored for any period of time were placed in amber containers.

Prior to testing, 40 gal of Well 410 groundwater was collected in high-density polyethylene (HDPE) plastic containers (5 gal each). Immediately after collection, these samples were transported to the onsite laboratory where equal portions from each 5-gal container were transferred to 40 amber glass containers (1 gal each). A representative sample was collected from two of the containers and was shipped to an offsite laboratory for analysis. The purpose of this sample was to verify the presence of explosive contaminants. Table 8 presents the average of 15 analyses for explosives in Well 410 water supply samples (the water used in the isotherm evaluations). Samples were stored in amber glass bottles at room temperature for 3 days prior to the initiation of the isotherm tests (until the results of the laboratory tests were obtained).

Table 8 Typical Well 410 Water Explosive Concentration	
Explosive Contaminant	Concentration, ppb
1,3,5-TNB	<DL
1,3-DNB	<DL
2,4,6-TNT	<DL
2,4-DNT	<DL
2,6-DNT	<DL
HMX	1.4
NB	<DL
RDX	5.5
TETRYL	<DL
Note: DL = Detection limit.	

The five carbons investigated for the adsorption of RDX and HMX are listed in Table 9. These carbons were pulverized by the manufacturers prior to testing to ensure that equilibrium conditions would be obtained quickly. A known weight of dry carbon was added to 1-ℓ amber glass bottles, and 850 ml of contaminated water from Well 410 was added to each bottle.

All glassware and containers contacting the samples were prewashed by first washing in a laboratory cleaning solution of soap (Alconox) and tap water. Then the containers were triple rinsed with American Society for Testing and Materials (ASTM) Type III water, followed by triple rinsing with double distilled deionized water that was passed through a carbon adsorption system.

The bottles containing the carbon and Well 410 contaminated water were sealed with Teflon caps. Nominal carbon-to-water dosage consisted of 10,

Table 9
Carbon Types Evaluated in Isotherm Tests

Manufacturer	Carbon Type	Base Material
Westates Carbon, Inc.	CC-601	Coconut Shell
Calgon Carbon Corp.	Filtrasorb 200	Bituminous Coal
Calgon Carbon Corp.	Filtrasorb 400	Bituminous Coal
American Norit Co.	Norit ROW 0.8	Extruded Coal
American Norit Co.	Hydrodarco 4000	Lignite Coal

100, 500, 1,000, 5,000, and 20,000 mg/ℓ. Because of the low concentration of explosives in the groundwater and possible analytical error, all tests were performed in triplicate, and a blank sample was carried through the isotherm tests for each carbon type. In addition, the pH of one set of the Filtrasorb 400 carbon was lowered to 4.0 to investigate the effects of pH on adsorption. Filtrasorb 400 was utilized since this is a very commonly used carbon for explosive treatment.

After the carbon and water were placed in the 21 containers (all samples for a single carbon type), they were placed on a Eberbach reciprocating shaker and shaken in the horizonal position at 166 cycles per minute for 24 hr at room temperature (26 ± 3 °C). Table 10 presents the isotherm test matrix.

Table 10
Isotherm Test Matrix for Granular Activated Carbon

24-Hr Isotherm Test	Number of Samples	Number of Variables
Isotherm tests to select best-performing GAC	105[1]	5 GACs 1 Temperature 1 Solution 7 GAC dosages[2] 1 pH[3] triplicates
Isotherm tests to determine effect of pH	21[1]	1 GAC 1 Temperature 1 Solution 7 GAC dosages[2] 1 pH[4] triplicates

[1] Each sample was analyzed for RDX and HMX.
[2] Seven varying GAC dosages (0, 10, 100, 500, 1,000, 5,000, and 20,000 mg/ℓ).
[3] No pH adjustment was performed.
[4] pH was 4.0.

Upon the completion of the 24-hr contact period, samples were removed from the shaker and the carbon was allowed to settle. The carbon was

separated from the liquid by passing it through a Millipore HAWP-047 0.45-μm filter using vacuum. The filtered samples were placed in 1-ℓ amber glass jars, sealed with Teflon caps, packed in ice, and shipped to an offsite laboratory for analysis. Each sample was analyzed for nine explosives according to USATHAMA's Method UW 26.

Pilot Study

Carbon column design

Two of the five carbons were selected for study in the pilot test (H-4000 and F-200). These carbons were selected because of their relative low cost, widespread use, availability, and the results of the isotherm tests. Sixteen 4-in. diam by 5-ft height plexiglass columns were built at WES. Four sets of columns were plumbed in series with 1/4-in. copper tubing. This provided four sets of four columns that operated in an upflow mode as shown in Figure 21. These columns were transported to PTA where they were set up in a mobile laboratory adjacent to the 410 well head. Prior to operation, each carbon column was filled with deionized water, and 4.87 kg (as received or wet weight) of F-200 and 3.76 kg (weight as received) of H-4000 were placed in these columns. This weight of carbon filled the columns to a height of 4 ft, leaving 1 ft of freeboard area. Two sets of four columns were filled with F-200, and the other two sets of four columns were filled with H-4000 as illustrated in Figure 21.
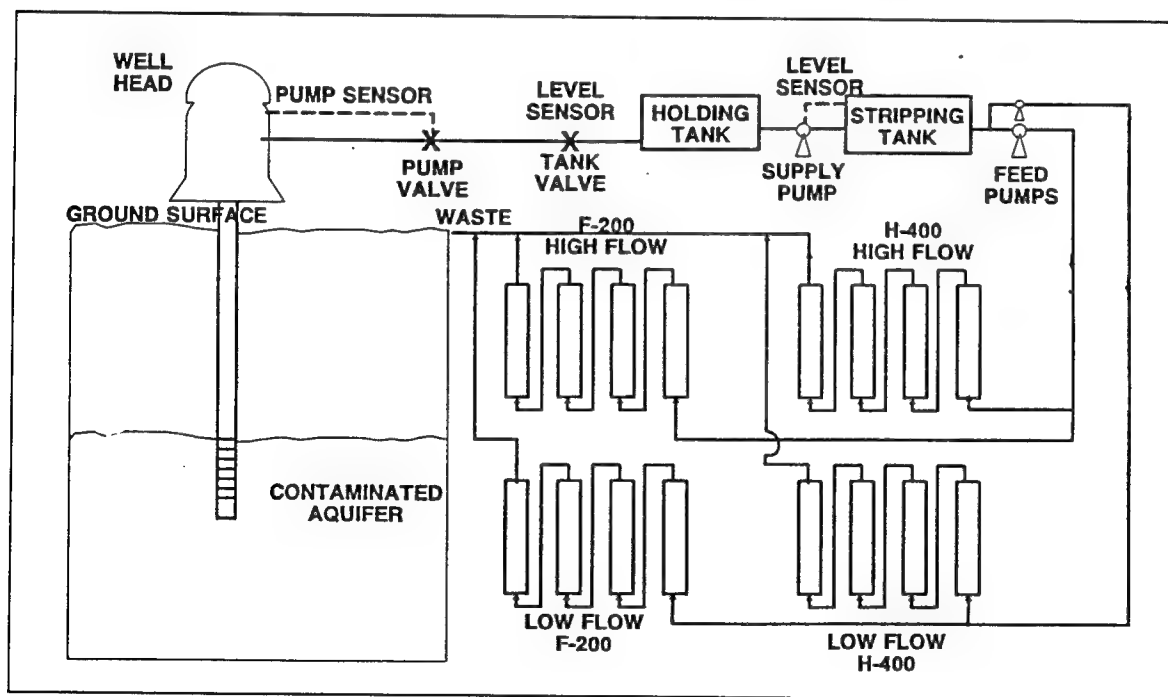
Figure 21. Pilot column study setup

Because the isotherm tests did not provide isotherm curves that could be used to predict the equilibrium sorption capacity of the carbon, no prediction of the length of time from the start of this test until the occurrence of breakthrough could be made (see the Results - Isotherm section of this report). In an effort to address this problem, the flow rate of water passing through one set of columns for each carbon was set at a recommended flow rate of 0.16 gal/min (American Norit Company, Inc. 1987). The flow rate of water passing through the remaining two sets of columns was set at a flow rate of 0.48 gal/min just prior to fluidizing the carbon bed. This provided two sets of low-flow columns (0.16 gal/min) and two sets of high-flow columns (0.48 gal/min) for each carbon. The experimental conditions for the GAC pilot column study are presented in Table 11.

Table 11
Experimental Conditions for Continuous-Flow Pilot Tests Using GAC

Column Set	Column	Carbon Type (a)	Flow Rate gpm	Hydraulic Loading gpm/ft^2	Bed Depth ft	Cumulative Contact Time, min
1	4	F-200	0.48	5.5	4	5.4
	3	F-200	0.48	5.5	4	10.8
	2	F-200	0.48	5.5	4	16.3
	1	F-200	0.48	5.5	4	21.7
2	12	H-4000	0.48	5.5	4	5.4
	11	H-4000	0.48	5.5	4	10.8
	10	H-4000	0.48	5.5	4	16.3
	9	H-4000	0.48	5.5	4	21.7
3	8	F-200	0.16	1.8	4	16.3
	7	F-200	0.16	1.8	4	21.7
	6	F-200	0.16	1.8	4	27.2
	5	F-200	0.16	1.8	4	32.6
4	16	H-4000	0.16	1.8	4	16.3
	15	H-4000	0.16	1.8	4	21.7
	14	H-4000	0.16	1.8	4	27.2
	13	H-4000	0.16	1.8	4	32.6

Note: Column diameter - 4.0-in. ID (0.333 ft); Column cross-sectional area - 0.08727 ft^2; Column volume - 0.349 ft^3.

System setup

A 1/2-in. tap was run from the 10-in. supply line from Well 410. This 1/2-in. tap supplied water to the pilot system as shown in Figure 22. Unfortunately, the Well Pump 410 was not operated on a continuous basis. Thus, a system to store water from Well 410 was required for this study. This system is described below.
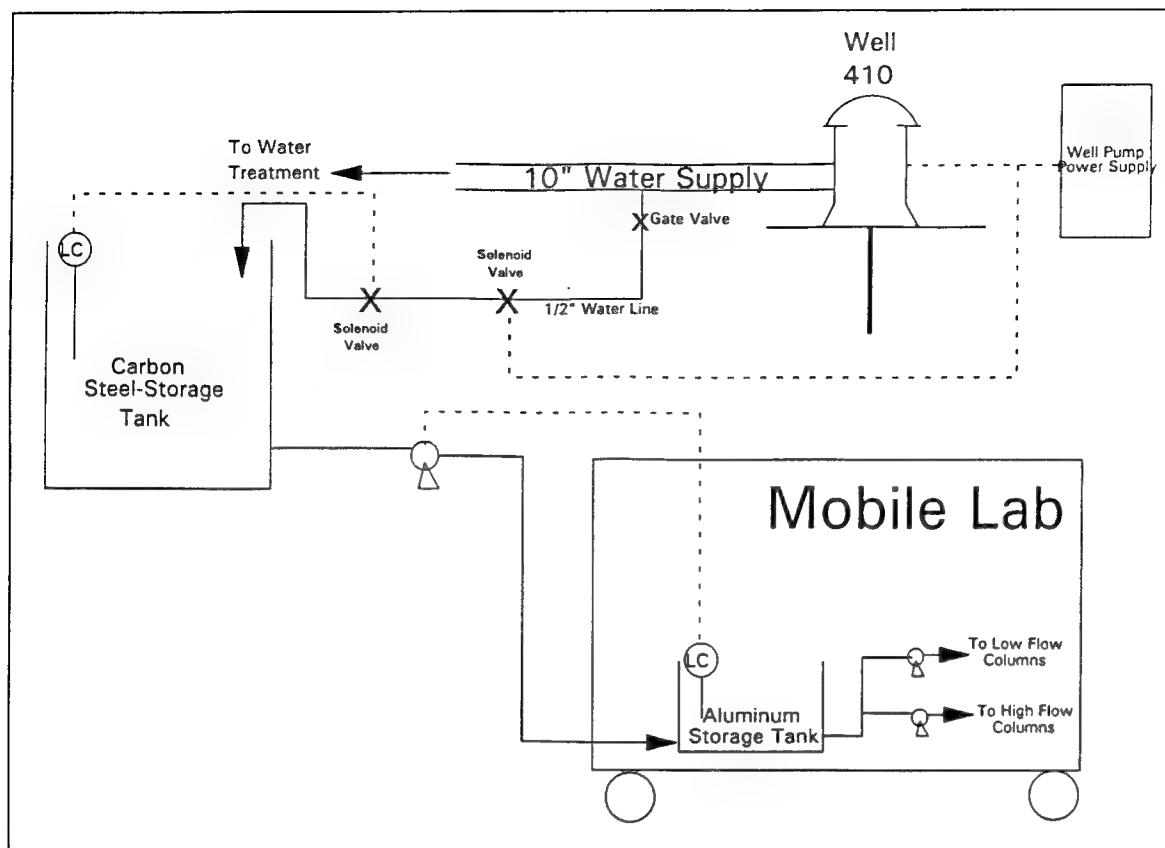
Figure 22. Water supply system to pilot column system

Arrangements were made to have Well 410 turned on every 12 hr and to operate for a minimum period of 1 hr. This required a 12-hr storage of Well 410 water for this study. A 3,000-gal carbon steel tank was used to provide this storage capacity. To maintain water in the tank, a level controller was installed in the tank, and a power sensor was installed on the power supply to the motor on Well 410. Two solenoid valves were placed in series in the 1/2-in. copper supply tap from the well head tap to the storage tank as shown in Figure 22. When the well pump was turned on, the first solenoid was energized and opened. In addition, when the water level in the tank dropped, the other solenoid was energized and the second valve was opened. Thus, when the tank level was low and the well pump was on, both valves were opened and the tank filled. This tank was also insulated and equipped with an immersion heater to keep the water in the tank from freezing during cold-weather periods.

Water from this large storage tank was pumped into a 300-gal aluminum tank located inside the mobile laboratory (Figure 22). The tank was baffled as shown in Figure 23. A level controller was installed in this aluminum tank that was connected to the supply pump for this tank. When the level of water dropped in the aluminum tank, the supply pump was energized and refilled the tank from the large storage tank containing 3,000 gal of Well 410 water. The small aluminum tank served many purposes. First, an oil-less air compressor
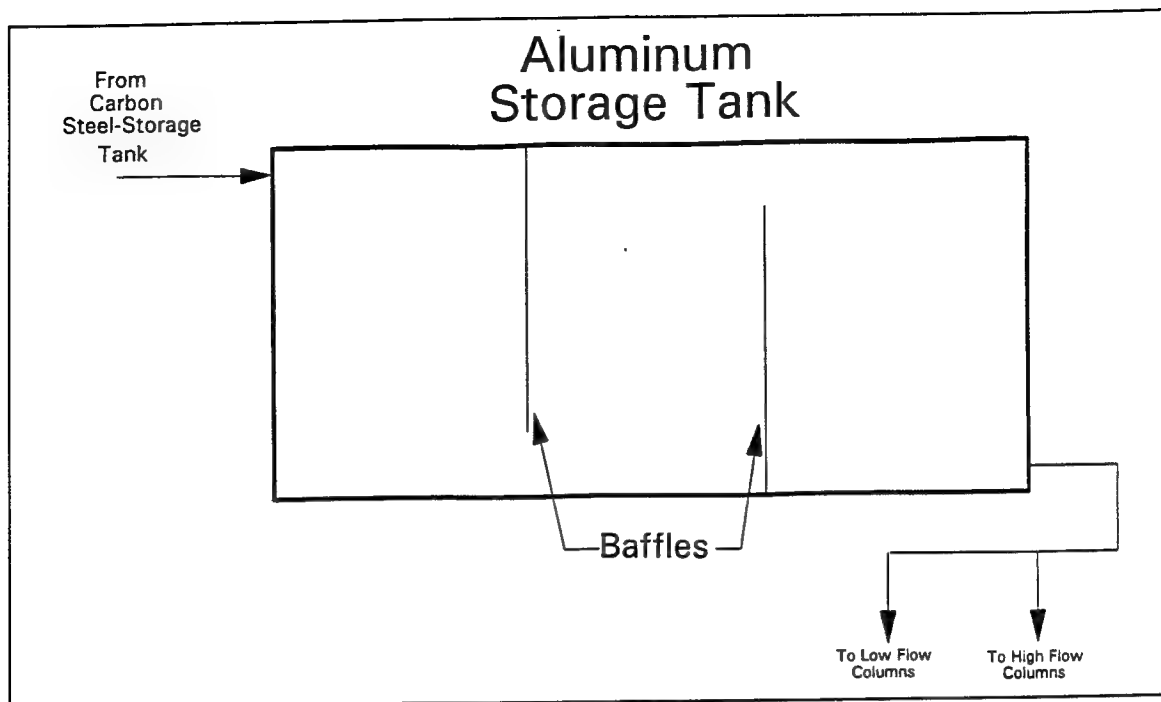
Figure 23. Map view of small 300-gal aluminum storage tank

was used to aerate the first two baffled areas of this tank. This served to strip any TCE from the water prior to carbon treatment. Second, the tank had a 3.5-hr retention period that provided temperature equalization because the temperature of the mobile laboratory was controlled. The tank was equipped with a continuous temperature recorder to monitor the water temperature of the feed supplied to the pilot carbon systems. Thirdly, the last baffle of the tank was not aerated. This provided an area of settling or quiescence that allowed any oxidized iron or particulates to settle out of the water and also provided for some deaeration.

Four stainless steel micropump gear pumps (model 120-000) were used to provide water flow from the small tank in the mobile laboratory to each carbon system. Each system was equipped with a dual continuous flow and flow totalizer meter (signet Accum-U-Flow models P57540R and MK575R). In addition, a Cole Parmer model G-03269-84 rotameter was installed in the water supply line of each low-flow column set and an Omega FL4601 rotameter was installed on the high-flow column sets.

Sampling

Samples were collected from the first and second columns of each carbon set daily. In an effort to reduce analytical expenses, these samples were stored at 4 °C for 2 weeks. At the end of the 2-week period, only the samples collected on the 13th and 14th days of sampling from the first column for each high-flow carbon set were shipped to the offsite laboratory for

analysis. Analytical results were provided within 2 weeks. If any detectable amounts of explosives were measured in these samples, the remaining stored samples would be shipped to the laboratory for analysis. If no detectable amounts of explosives were measured, the stored samples would be discarded and the 2-week sampling cycle would be repeated. This ensured that no samples would be older than 45 days prior to analysis (the allotted holding time for samples in this study). In addition, periodically, influent samples were collected to monitor the level of explosive contained in the influent water supplied to the columns. All samples were stored in 1-ℓ amber prewashed bottles sealed with Teflon caps and analyzed for explosives according to ADL's method UW26.

If breakthrough was not observed in the low-flow carbon systems after a period of 8 weeks, the operation of the low-flow carbon systems would be terminated. If breakthrough was observed by the 8th week in the first column of the low-flow carbon columns, the operation of the high-flow columns would be terminated. This operational setup ensured that the breakthrough front could be tracked whether it was as a slow-moving or fast-moving front.

3   Results

Isotherm Tests

The results of the isotherm tests were averaged for the three runs and are presented in Table 12. Detailed analytical results along with the quality control data are provided in Appendix C. All the carbons at each dosage tested produced results below the detection limit of 0.617 ppb for RDX and 0.869 ppb for HMX. Normally, isotherm tests are modeled with either Lagmuir or Freundlich equations as discussed in the Introduction section of this report. This type of examination provides an estimate of the ultimate adsorption capacity that carbon has for the contaminant (Weber 1972; Clark and Lykins 1989). Unfortunately, in this study all the data points were below the detection limit. As a result, isotherm analysis is not available.

Because the 18 control samples analyzed for the untreated Well 410 water had concentrations ranging from 5.4 to 6.1 ppb of RDX, it can be said with a high degree of certainty that the carbons tested were very effective in removing the RDX from the drinking water samples. Prior to conducting these isotherm tests, the carbons were not expected to have a high sorptive capacity for the RDX in the dilute drinking water. Isotherm curves, if they could have been generated, would have helped to identify the carbons with the largest absorption capacity for the RDX; but no isotherm could be plotted, and the best performing carbons could not be selected.

Consideration was given to possibly retesting the carbons using even smaller carbon dosages. Such testing would be difficult to conduct. The carbon-to-water dosages would be required in the range of less than 1 mg of carbon per liter of water. Utilizing a standard laboratory analytical balance with 0.0001-g accuracy would have required at least a 10-ℓ container to maintain a minimum of two significant figures accuracy. Fewer significant figures would have generated meaningless data. After careful consideration, it was decided that any benefit from such testing would be minimal.

Based on the fact that all the carbon types tested were effective, it was decided to select the less expensive and more common carbon types that have widespread use and good availability for pilot-scale testing. Observations

Table 12		
Results of Isotherm Tests		
Concentrations		
Carbon, mg/ℓ	HMX, ppb	RDX, ppb
F-200		
BL	1.62	5.77
10	<0.869	<0.617
100	<0.869	<0.617
500	<0.869	<0.617
1,000	<0.869	<0.617
10,000	<0.869	<0.617
F-400		
BL	1.88	6.04
10	<0.869	<0.617
100	<0.869	<0.617
500	<0.869	<0.617
1,000	<0.869	<0.617
10,000	<0.869	<0.617
pH = 4.0	1.630	5.48
BL	<0.869	<0.617
10	<0.869	<0.617
100	<0.869	<0.617
500	<0.869	<0.617
1,000	<0.869	<0.617
10,000		
CC-601		
BL	0.523	4.53
10	<0.869	<0.617
100	<0.869	<0.617
500	<0.869	<0.617
1,000	<0.869	<0.617
10,000	<0.869	<0.617
ROW 0.8		
BL	1.38	5.78
10	<0.869	<0.617
100	<0.869	<0.617
500	<0.869	<0.617
1,000	<0.869	<0.617
10,000	<0.869	<0.617
H-4000		
BL	1.72	5.42
10	<0.869	<0.617
100	<0.869	<0.617
500	<0.869	<0.617
1,000	<0.869	<0.617
10,000	<0.869	<0.617

Note: F-200 = Filtrasorb 200; F-400 = Filtrasorb 400; Row 0.8 = Norit ROW 0.8; H-4000 = Hydrodarco 4000; CC-601 = Westates Carbon CC-601.

regarding the data from isotherm test performed at a low pH (4.0) provided no additional insight into the benefit of reducing the pH to increase adsorption of RDX. Thus, it was decided to utilize the Calgon F-200 and H-4000 carbons without pH adjustment in the pilot column tests.

Pilot Column Tests

The pilot carbon column testing was initiated on 28 August 1991. Since no explosives were detected in the column effluent after 8 weeks of operation, the operation of the low-flow columns was terminated on 10 October 1991. A total of 612 samples were collected from the high-flow columns and 92 samples were analyzed for explosives. The RDX and HMX results are summarized in Table 13. The complete analyses as well as the quality control data are presented in Appendix D. As indicated in this table, no detectable amount of explosives was measured in any of the samples collected after approximately 70,000 gal of contaminated water had passed through the carbon columns as of 05 March 1992. Analysis of influent samples indicated that the concentration of RDX and HMX fed to the columns was relatively consistent.

Because all of the samples collected after carbon treatment (as of 05 March 1992) were below the detection limit, no prediction could be made of the length of testing that would be required prior to observing breakthrough in the first column. On 11 February 1992, a meeting was held with PTA Environmental and Water Treatment personnel and the WES study team to discuss concerns regarding the need for breakthrough data and the length of the pilot test. In an effort to address this concern, the WES study team suggested the possibility of modifying the first column of the high-flow F-200 system. PTA agreed to this the recommendation. This modification would serve to speed test results without compromising test results.

The first column was modified by drilling through the plexiglass column every 6 in. and attaching a valved sampling port to the column as shown in Figure 24. Samples were collected from these sampling ports, and a breakthrough front was established. The data from the first sampling effort after the installation of these sampling ports is shown in Figure 25. Sampling of this column continued although leaking of the 24-in. port required it to be sealed shut. On 26 June 1992, the first column of the high-flow H-4000 system was also modified. Ports were installed at 6, 12, 24, and 30 in. from the bottom of the column. Samples were collected from these ports and analyzed. Operation and sampling of these columns continued until 29 June 1992 when operation of the pilot system was terminated.

Table 13
Summary of RDX and HMX Results for Column Study

Date	Column	Water Flow Rate	Carbon Type	RDX	HMX
09/12/91	1	High Flow	F-200	<0.617	<0.869
09/12/91	2	High Flow	F-200	<0.617	<0.869
09/12/91	9	High Flow	H-4000	<0.617	<0.869
09/12/91	10	High Flow	H-4000	<0.617	<0.869
09/13/91	4	High Flow	F-200	<0.617	<0.869
09/13/91	12	High Flow	H-4000	<0.617	<0.869
10/02/91	4	High Flow	F-200	<0.617	<0.869
10/02/91	12	High Flow	H-4000	<0.617	<0.869
10/14/91	4	High Flow	F-200	<0.617	<0.869
10/14/91	12	High Flow	H-4000	<0.617	<0.869
10/15/91	4	High Flow	F-200	<0.617	<0.869
10/15/91	12	High Flow	H-4000	<0.617	<0.869
10/31/91	3	High Flow	F-200	<0.617	<0.869
10/31/91	4	High Flow	F-200	<0.617	<0.869
10/31/91	11	High Flow	H-4000	<0.617	<0.869
10/31/91	12	High Flow	H-4000	<0.617	<0.869
12/04/91	4	High Flow	F-200	<0.617	<0.869
12/04/91	12	High Flow	H-4000	<0.617	<0.869
12/05/91	4	High Flow	F-200	<0.617	<0.869
12/05/91	12	High Flow	H-4000	<0.617	<0.869
12/18/91	4	High Flow	F-200	<0.617	<0.869
12/18/91	12	High Flow	H-4000	<0.617	<0.869
12/19/91	4	High Flow	F-200	<0.617	<0.869
12/19/91	12	High Flow	H-4000	<0.617	<0.869
01/01/92	4	High Flow	F-200	<0.617	<0.869
01/01/92	12	High Flow	H-4000	<0.617	<0.869
01/02/92	4	High Flow	F-200	<0.617	<0.869
01/02/92	12	High Flow	H-4000	<0.617	<0.869
01/15/92	4	High Flow	F-200	<0.617	<0.869
01/15/92	12	High Flow	H-4000	<0.617	<0.869
01/16/92	4	High Flow	F-200	<0.617	<0.869
01/16/92	12	High Flow	H-4000	<0.617	<0.869
01/29/92	4	High Flow	F-200	<0.617	<0.869
01/29/92	12	High Flow	H-4000	<0.617	<0.869
01/30/92	4	High Flow	F-200	<0.617	<0.869
01/30/92	12	High Flow	H-4000	<0.617	<0.869
08/29/91	INFLUENT	High Flow		5.44	1.4
08/12/91	INFLUENT	High Flow		5.21	1.26
10/02/91	INFLUENT	High Flow		5.25	1.23
11/01/91	INFLUENT	High Flow		5.01	1.26
12/05/91	INFLUENT	High Flow		4.44	1.21
12/19/91	INFLUENT	High Flow		4.59	1.2
01/02/92	INFLUENT	High Flow		3.91	1.11
01/30/92	INFLUENT	High Flow		4.38	1.23
02/19/92	INFLUENT	High Flow		4.03	1.15
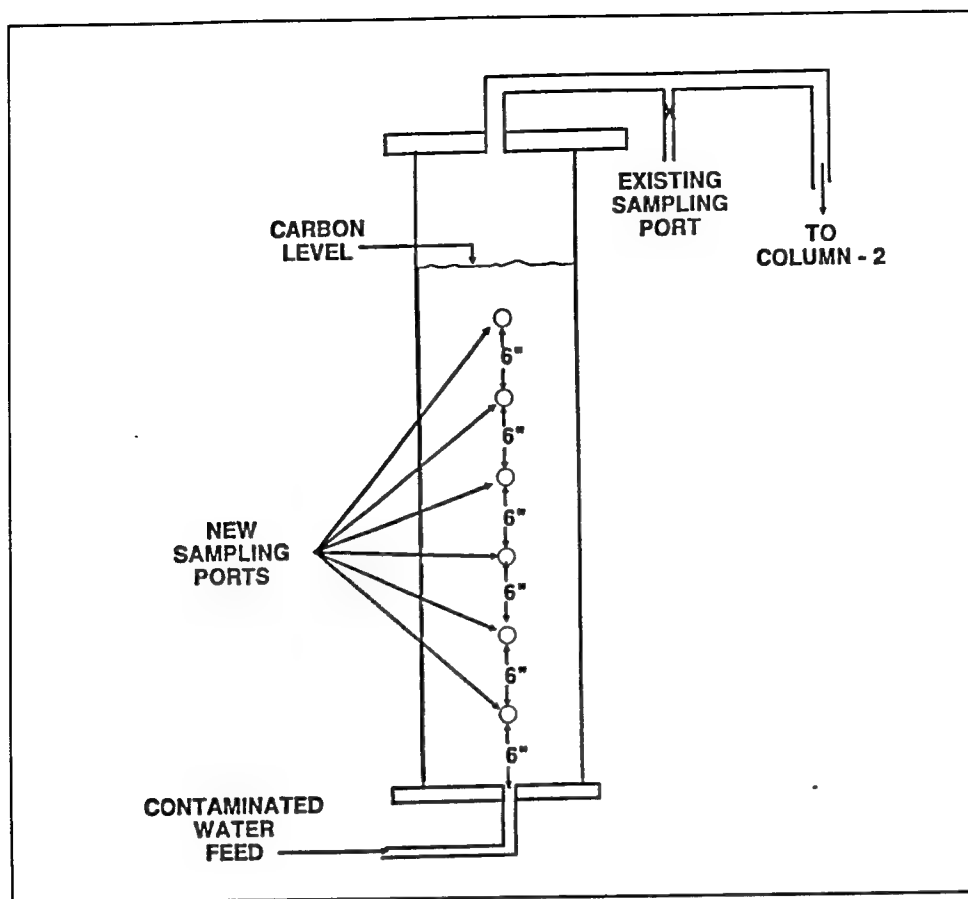
Figure 24. Modified column with valved sampling ports

Modified Column Results

Results from the modified columns are summarized in Table 14. Detailed analytical results along with the quality control data for the modified columns are provided in Appendix D.

As shown in Figure 16, the contaminant front is tracked through each column as time or the volume of liquid that has contacted the column increases. Because of the urgent need for the data, the experiment could not be conducted for the length of time it would have required to develop such curves for each column. As indicated in the Introduction section of this report, no previous studies that discussed the treatment of low levels of munitions in aqueous solutions could be identified in the open literature; thus the experimenters did not have information to indicate how long this test might take. The results of the isotherm studies indicated that RDX is effectively absorbed by carbon when equilibrium conditions are established, but questions regarding the kinetics of adsorption were unanswered by the isotherm and literature investigations. Prior to the initiation of the carbon pilot study, it was believed
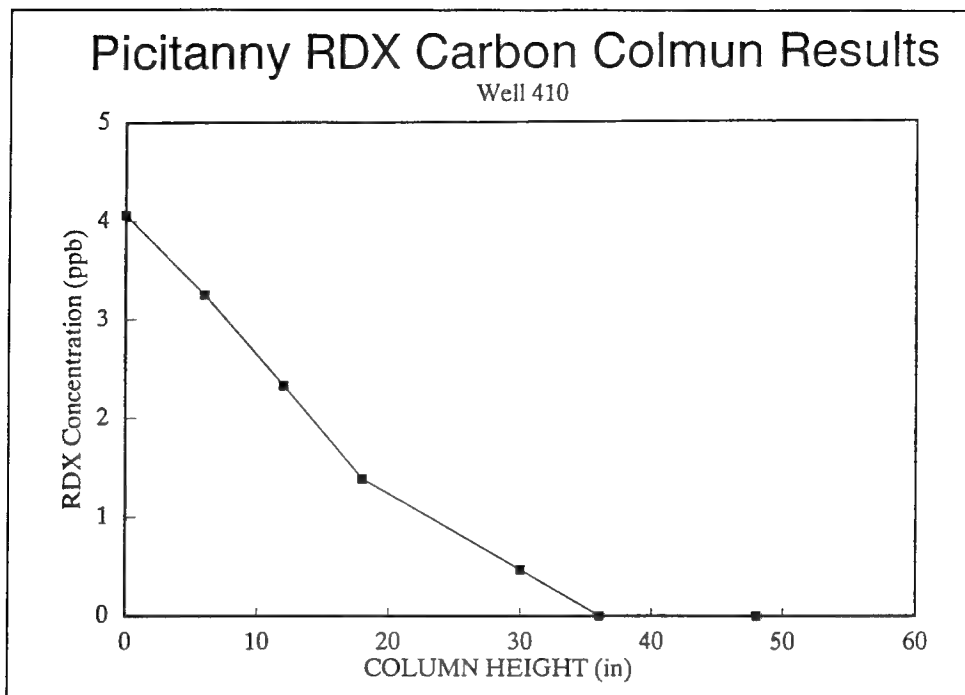
Figure 25. First sampling of F-200 modified column, 05 March 1995

that the kinetics of absorption would be slow because of the dilute nature of the RDX. Based on this information, the calculated RDX breakthrough was expected to occur in 2 to 3 months after the study was initiated. Breakthrough did not occur as expected; in fact, the test ran almost a year, and break- through in the first column for both carbon systems was not detected.

As a result of this lenghtly time to achieve breakthrough, fewer GAC regeneration cycles in the full-scale treatment system will be required. This will result in lower material and operational costs. Unfortunately, from a scientific viewpoint, this requires the pilot study to be performed for longer periods of time; if the test is cut short (as this study was), few data points are obtained. Because of the lack of data, it was impossible to analyze the pilot data using classical carbon methodology (Foust and Aly 1987). An alternative technique to the classical approach was the use of the modified column.

The modified column provides a unique tool that can be used for this study. By installing sampling ports in the column, the large 4-ft column is subdivided into small 6-in. columns. A single sampling of each port provides a "snapshot" of the GAC exhaustion curve. This snapshot is represented by the vertical line on a classical exhaustion curve (labeled study data) as shown in Figure 16. A single sampling of each port provides some limited insight regarding carbon exhaustion. If many samples are collected from each of the modified column's ports over an extended period of time, the portions of the exhaustion curve can be generated. Such a curve for this study for the period of 05 March 1992 to 29 June 1992 is presented in Figure 26. This is a plot

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Table 14
Summary of RDX and HMX Results for Modified High-Flow Column

Date	Column	Port Height	Carbon Type	RDX, ppb	HMX, ppb
03/05/92	Influent			4.06	1.05
	4	6	F-200	3.25	0.855
	4	12	F-200	2.33	0.552
	4	18	F-200	1.39	<0.434
	4	24	F-200	0.777	<0.434
	4	30	F-200	0.471	<0.434
	4	36	F-200	<0.309	<0.434
04/17/92	Influent			3.69	0.838
	4	6	F-200	3.18	0.675
	4	12	F-200	2.7	0.541
	4	18	F-200	2.2	0.468
	4	30	F-200	1.05	<0.434
	4	36	F-200	0.587	<0.434
05/29/92	Influent			4.3	0.955
	4	6	F-200	3.43	0.803
	4	12	F-200	2.47	0.57
	4	18	F-200	1.93	<0.869
	4	30	F-200	1.02	<0.869
	4	36	F-200	0.618	<0.869
	Effluent			<0.617	<0.869
06/23/92	Influent			4.06	1.08
	4	6	F-200	3.67	1.02
	4	12	F-200	2.98	0.807
	4	18	F-200	2.19	0.601
	4	30	F-200	1.32	<0.869
	4	36	F-200	0.8	<0.869
	Effluent			<0.617	<0.869
06/26/92	Influent			4.24	1.31
	11	6	H-4000	1.89	0.589
	11	12	H-4000	0.762	<0.869
	11	24	H-4000	<0.617	<0.869
	11	30	H-4000	<0.617	<0.869
	Effluent			<0.617	<0.869
06/29/92	Influent			4.24	1.13
	4	6	F-200	3.83	0.998
	4	12	F-200	3.22	0.796
	4	18	F-200	2.76	0.609
	4	30	F-200	1.66	<0.869
	4	36	F-200	1.08	<0.869
	Effluent			<0.617	<0.869
06/29/92	Influent			4.25	1.22
	11	6	H-4000	2.99	0.86
	11	12	H-4000	1.84	0.517
	11	24	H-4000	0.395	<0.869
	11	30	H-4000	<0.617	<0.869
	Effluent			<0.617	<0.869
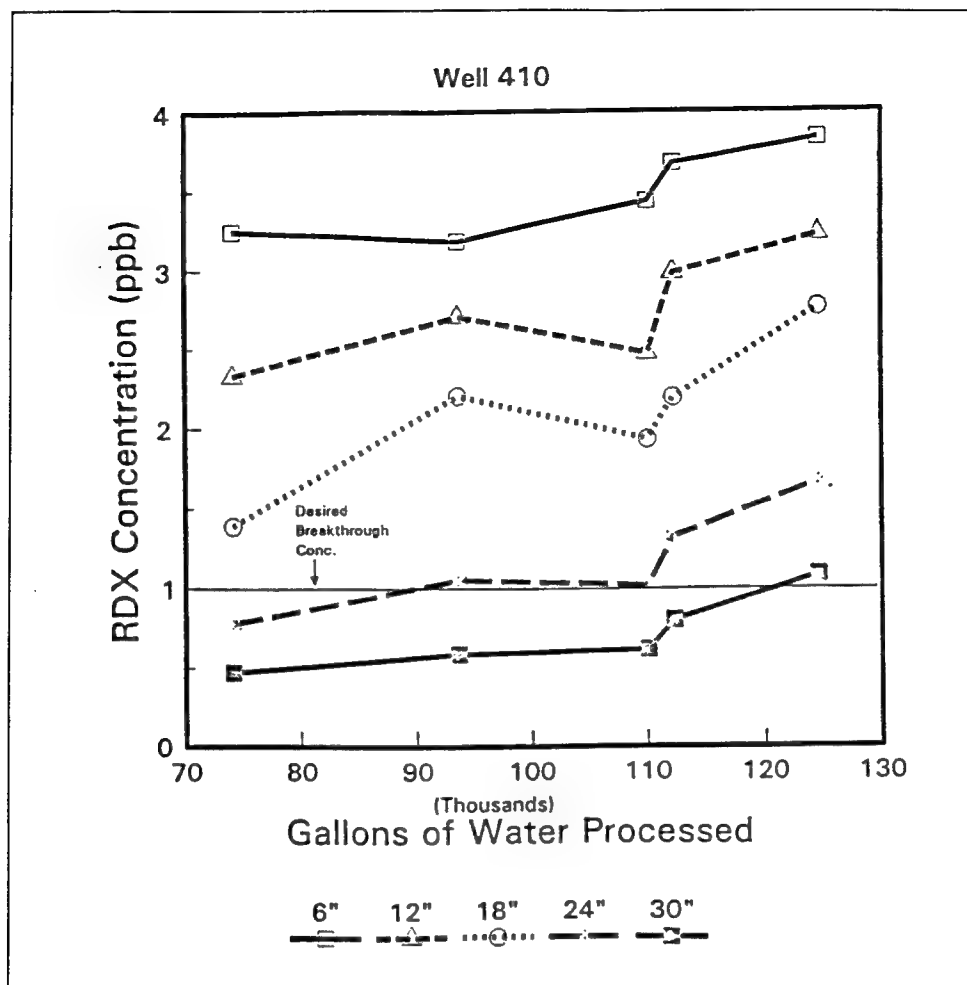
Figure 26. RDX concentration versus gallons of water processed for F-200 modified column covering sampling period, 05 March 1992 - 29 June 1992

of the volume of RDX-contaminated water that has passed through the column versus RDX concentration at each sampling port. Each line represents the concentration over time for a single port. When the sampling of the modified column was started (at approximately 70,000 gal of water), the MTZ had achieved breakthrough at a height of 18 in. As more water was passed through the column and additional samples were collected, breakthrough was observed at 24 in. after 90 gal of water passed through the column and at 30 in. for 120 gal. Assuming a constant rate of movement for the MTZ, extrapolation of this data indicates that 240 gal of water must flow through the column prior to observing breakthrough at the 4-ft carbon level of the first column.

Another approach in interpreting the modified column data is simply to track the contaminant front through the column. By plotting the contaminant concentration versus column height, the contaminant front is mapped. This is illustrated using the data collected on 05 March 1992 from the high-flow

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F-200 column in Figure 25. In this figure, it is clear that breakthrough on 05 March 1992 occurs in the column between 20 and 25 in. (using the break-through criteria of 1 ppb RDX). Figure 27 is a plot of the contaminant fronts for all the sampling periods for the F-200 column. As illustrated by this figure, there is a general trend for the breakthrough front to move up the column with time, as expected. While generally it is expected that the curves should not overlap, the curves in the figure overlap because of the variation in RDX concentration in the influent over time.

Picitanny RDX Carbon Colmun Results
Well 410
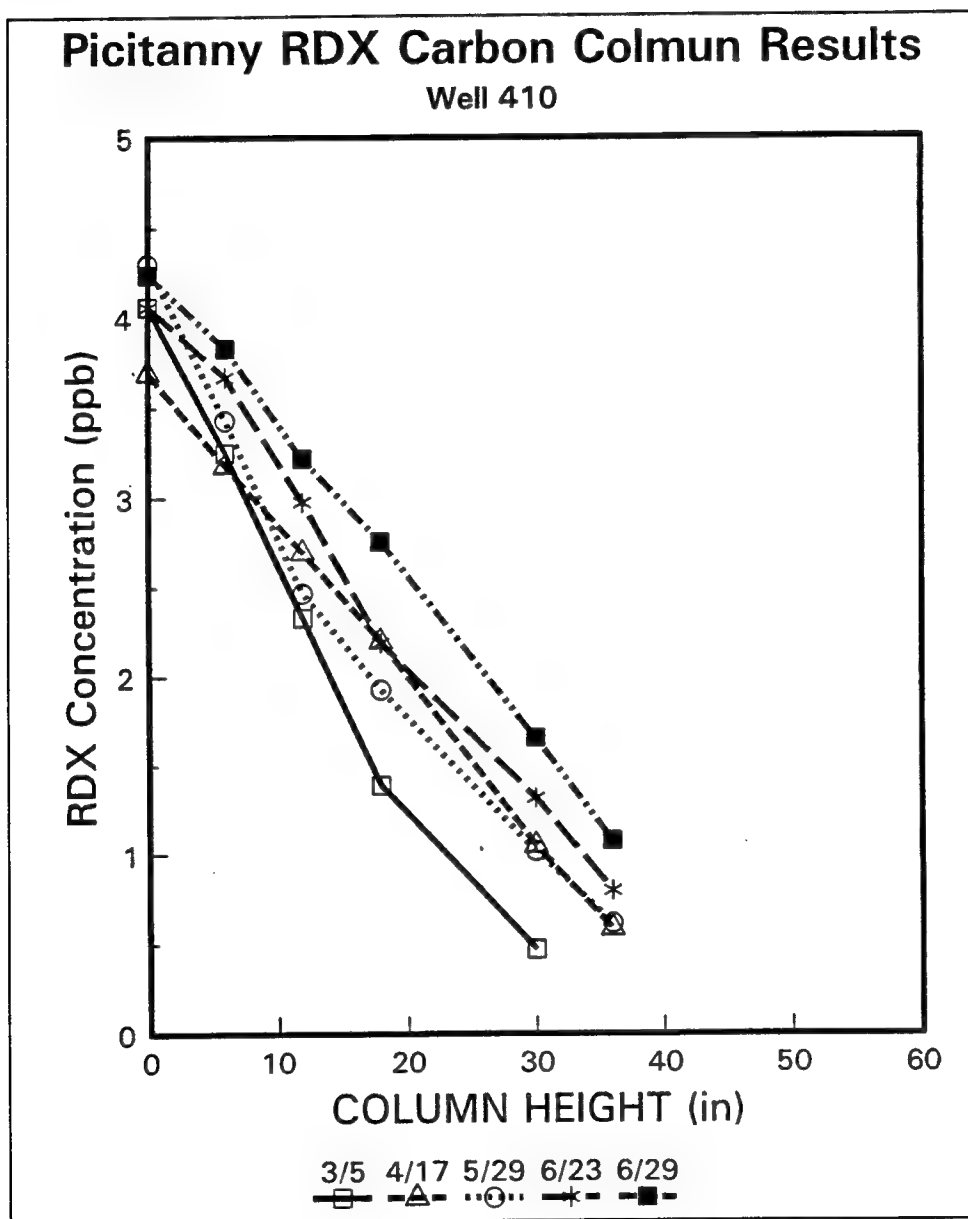
Figure 27. RDX concentration versus column height for F-200 modified column covering sampling period, 05 March 1992 - 29 June 1992

Design Approach

Two approaches can be used to generate design and operation criteria for the full-scale carbon treatment facility based on the pilot study data: the EBCT approach explained by Foust (Foust and Aly 1987) and the carbon usage rate based on breakthrough approach.

Empty bed contact time approach

Based on the modified carbon column data presented in Table 15 and using a breakthrough criteria of 1 ppb RDX, the data at breakthrough conditions can be extracted as presented in Table 16. Defining EBCT as shown in Equation 5, the data summarized in Table 16 can be calculated.

$$EBCT = \frac{Carbon\ Bed\ Volume\ (ft^3)\ *\ 7.48}{Flow\ rate\ (gal/min)} \tag{5}$$

Table 15
Modified F-200 High-Flow Column Data at Breakthrough Conditions

Date	Column Height, in.	Gallons Processed	Carbon Bed Volume, ft³	Time Operated days	Avg. Flow Rate gal/min
03/05/92	18	74,109	0.1309	180	0.286
04/17/92	30	93,643	0.2182	222	0.293
06/29/92	36	124,628	0.2618	289	0.299

Table 16
Height of Calgon F-200 Required to Remove RDX Concentration to 1 ppb at Each Sampling Period Based on Regression Results (Total volume of water carbon has contacted is also presented)

Date	Total Flow, gal	Carbon Height, in.
05 Mar 92	74,109	23.9
17 Apr 92	93,643	31.2
29 May 92	110,088	30.0
23 Jun 92	122,267	33.2
29 Jun 92	124,628	37.3

Note: Breakthrough criteria = 1 ppb of RDX.

(Details of these calculations are presented in Appendix F). The EBCT used for the design of the full-scale carbon absorber unit is taken from the plot of carbon usage rate versus the EBCT as presented in Figure 31. Typically,

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after an initial rapid decrease in carbon usage rate with increasing EBCT, the curve flattens. No significant reduction in carbon usage is gained with increasing contact time as illustrated by the typical curve (Figure 28). This phenomenon is not observed for the data collected from the modified high-flow F-200 pilot column. The data for this study (actual data in Figure 28) show little change in carbon usage with changing EBCT. This phenomenon can be attributed to the fact that the carbon was effective in removing the RDX and that limited data were available. Additional data would have added to the data interpretation, but the test had to be cut short; thus the data are compressed, only covering a 3-month period.
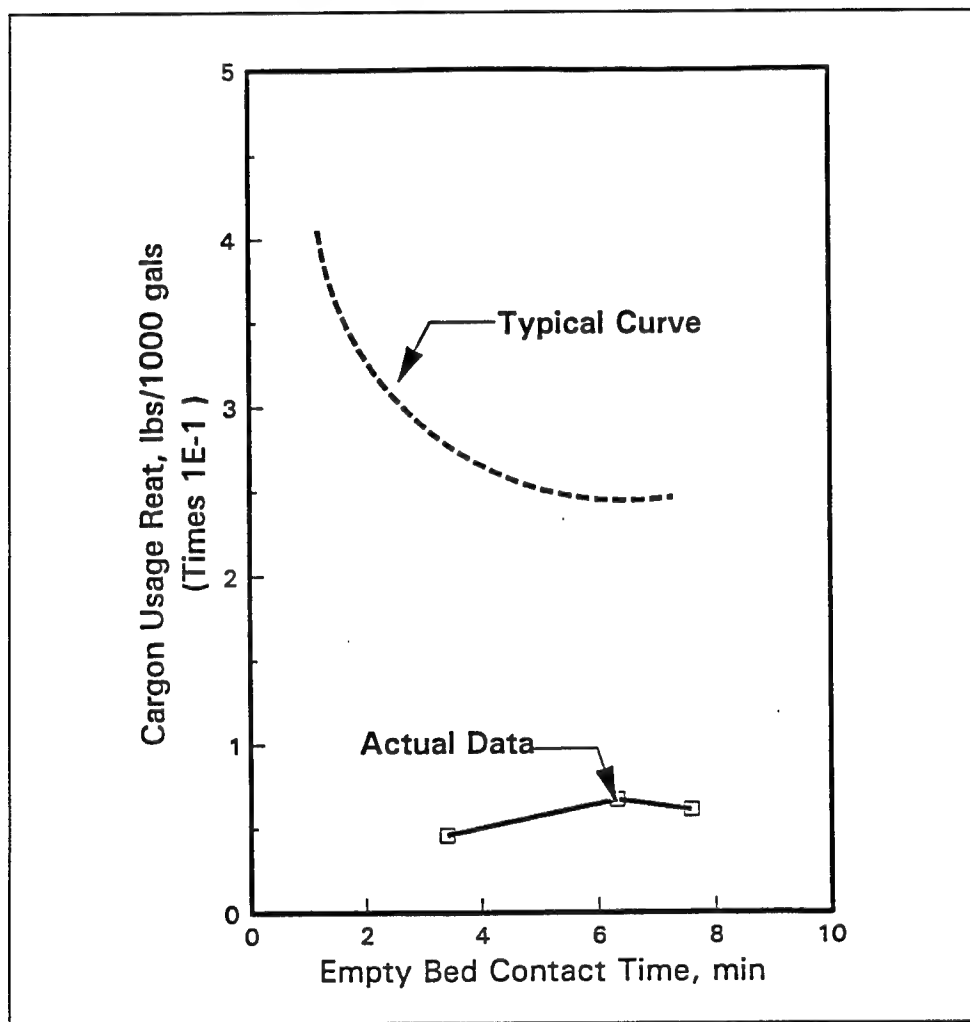
Figure 28. Carbon usage rate versus EBCT for modified F-200 column

Using the available data, an optimal EBCT of 3.38 min was selected from Figure 28 for the F-200 carbon. (As presented in Table 14, insufficient data were obtained by this study for the H-4000 carbon EBCT analysis.) Using an EBCT of 3.38 min, calculations indicate a carbon volume of 313 ft^3 is required for optimal RDX treatment (Appendix E). Using this carbon volume

and a hydraulic loading of 5.74 gal/minute/square foot (a maximum loading prior to fluidization), a 12.4-ft diam carbon absorber 2.6 ft tall is specified.

Carbon usage rate based on breakthrough approach

F-200. Table 16 presents the height and volume of F-200 carbon required to treat the RDX-contaminated drinking water. These data were generated using the data collected from the modified F-200 high-flow column from 03 March 1992 - 29 June 1992. A regression procedure is explained below.

Using the effluent concentration of 1 ppb RDX as a breakthrough criteria, the height of carbon in the column that is required to remove the RDX to 1 ppb was calculated. Because none of the samples collected had an exact concentration of 1 ppb RDX, the height of carbon at breakthrough was calculated using the aid of linear regression as a data fitting technique. Regression data as well as calculated data versus the actual data are presented in Appendix F.

Figure 29 is a plot of the volume of treated water versus the height of carbon used to treat the RDX. As illustrated in this plot, the data are slightly scattered as expected. By drawing a straight line through the data, one can
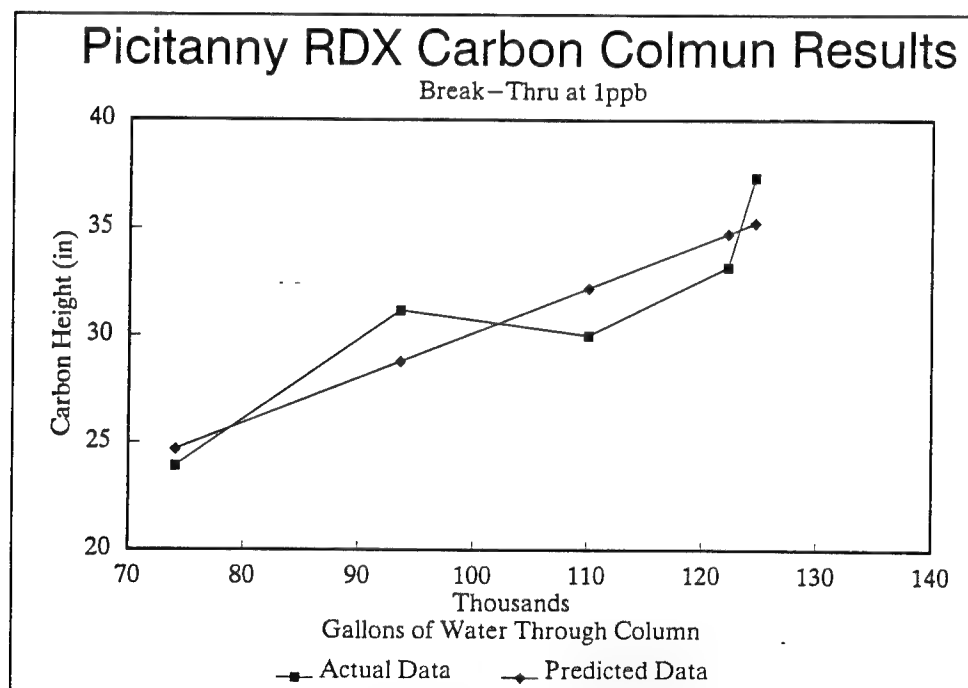
Figure 29. Volume of water passed through column at a breakthrough of 1 ppb versus carbon column height

see that while the data are scattered, a straight line is a fair approximation. The equation of this regression line is:

$$Y = (0.000209 * X) + 9.1909$$

where

Y = height of carbon required at breakthrough

X = gallons of treated water

The R^2 value (or the coefficient for the "goodness of fit") is 0.8125 where 1.0 is perfect. Thus, using the last point on this curve (the 29 June 1992 data at 37.3 in. of carbon and 124,628 gal of water at breakthrough) to represent treatment, 2.05 ft^3 of dry carbon is calculated to be needed to treat 1 million gallons of Well 410 contaminated water for the full-scale carbon treatment unit (these calculations are shown in Appendix G).

H-4000. Using the data collected for the high-flow H-4000 modified column from 27 June 1992 to 29 June 1992 (presented in Table 14) and the regression procedure described above for the F-200 carbon, the carbon height at breakthrough for the H-4000 carbon was calculated. Table 17 summarizes these regression results for the H-4000 where the height and volume of H-4000 carbon required to treat the RDX-contaminated drinking water are presented. The regression indicates that 19.12 in. of H-4000 carbon is required to treat the 73,591 gal of contaminated drinking water. Using this

Table 17
Height of American Norit H-4000 Required to Remove RDX Concentration to 1 ppb at Each Sampling Period Based on Regression Results (Total volume of water carbon has contacted is also presented)

Date	Total Flow, gal	Carbon Height, in.
27 Jun 92	72,748	10.5
29 Jun 92	73,591	19.1
Note: Breakthrough criteria = 1 ppb of RDX.		

information, a carbon usage rate for the H-4000 material is calculated at 1.99 ft^3 of dry carbon needed to treat one million gallons of Well 410 contaminated water for the full-scale carbon treatment unit (these calculations are shown in Appendix H). Because the F-200 and H-4000 carbons have similar carbon usage rates of 2.05 and 1.99 ft^3/million gallons, respectively, and that more data on the performance of the F-200 are available, full-scale treatment design and cost estimates are based on the F-200 performance.

Influent Analysis

While it is beyond the scope of this study to determine the source of explosive contamination for Well 410, an interesting observation was made. When the test was initiated, Well 410 pump was operated only once per 12-hr period and had been operated in this mode for several months. Because of well screen clogging, the pumping capacity of Well 129 dropped. To meet the water demand requirement of the PTA, it was necessary to operate the pump at Well 410, 20 to 24 hr per day.

Influent sampling (or sampling of Well 410 water) for this study from August 1991 to April 1992 indicated a steady decrease of RDX and HMX (Figure 30). This phenomenon may be attributed to one of two scenarios. First, a decrease in contaminant concentration might be observed if the source of contamination had been removed (or completely leached) and the center of the contamination plume has migrated past Well 410. Although unlikely, if this scenario represents actual conditions, the contamination levels of RDX and HMX should drop to less than the detection limit and no longer pose a drinking water health risk. Second, water removed at 300 gal per minute for an extended period of time from Well 410 substantially increases groundwater flow in aquifer A5 (Figure 5). As illustrated in the carbon isotherm studies, RDX and HMX are highly adsorbable at the concentration found in the groundwater. It is expected that the organic carbon and clays in the soil
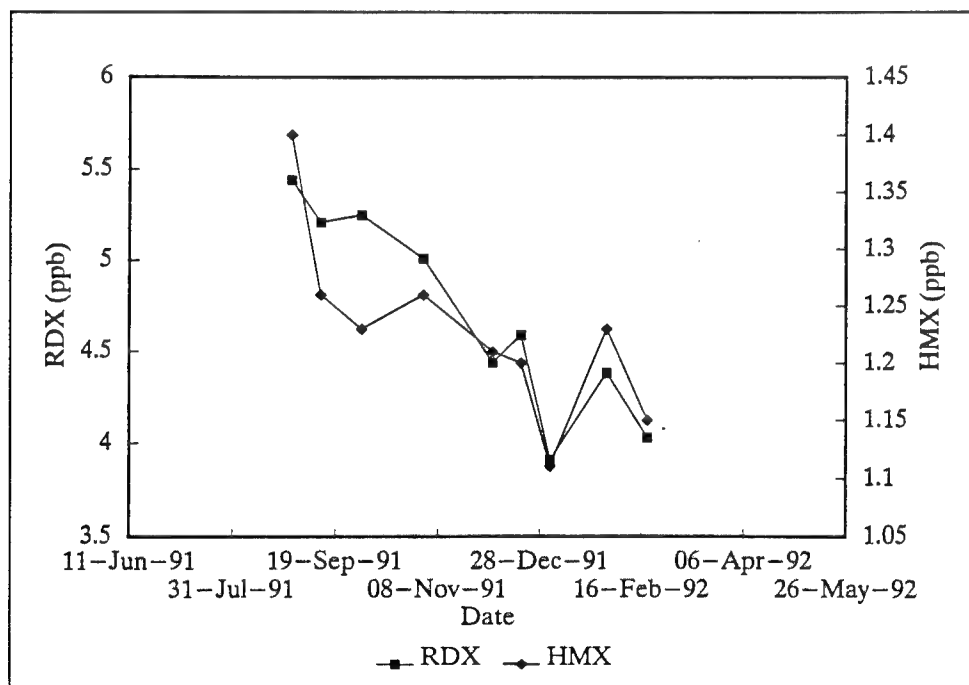
Figure 30. Influent concentration of RDX and HMX, August 1991 - April 1992

tightly adsorbed the RDX and HMX. If equilibrium adsorption conditions are established (as when stagnant water contacts the soil for an extended period of time), RDX and HMX desorbs from the soil and can concentrate in the groundwater to 4 to 5 ppb. When the flow of groundwater is increased (as when Well 410 is pumped for long periods of time), the groundwater flows too fast for equilibrium conditions to be established; thus RDX and HMX are diluted by fresh water, and their concentration drops. It is suspected if Well 410 is not utilized for an extended period of time or if the flow demand from this well is lowered, RDX and HMX concentrations will once again increase to 6 ppm or higher of RDX. Conversely, if the water demand at Well 410 continues, the RDX concentration is expected to continue to decrease or stabilize at reduced levels.

Preliminary Design of Full-Scale Treatment Systems

After the data were collected from the pilot carbon system, a preliminary design for the carbon system was initiated to be used for planning and cost-estimating purposes. Because the mission of WES is not directed toward design and WES has few staff design engineers, outside design expertise was sought to assist in the design of the carbon treatment system. WES contacted engineers at the Omaha District Corps of Engineers to assist in the design of the carbon treatment system. Ms. Jenelle Mabis, Omaha District, was the original point of contact for the design effort. A copy of the letter requesting this work to be initiated is provided in Appendix I. As a result of hurricane Andrew and the tragedy in Miami, FL, Ms. Mabis was assigned to support the recovery effort in Miami. In her absence, Mr. Mark Wichman, Omaha District, was assigned to the project and provided the design.

As provided in the 23 August 1992 letter to Ms. Mabis (Appendix I), a conservative figure for carbon usage of 1.50 ft^3 of carbon per million gallons of treated (versus the 2.05-ft^3/mg figure from the pilot study) was used for design. This carbon usage figure was utilized since this design was initiated prior to the completion of the study and more accurate data were not available at the time this design was initiated. Subsequent conversations with the Omaha District suggested that the capital costs associated with the carbon treatment plant would not change because they are based on a plant designed using hydraulic retention time and not carbon usage.

Another design modification that varies from the carbon pilot results is the size of the carbon absorber. As calculated using the EBCT approach, carbon absorber (12.4-ft diam and 2.6-ft-tall) is specified. A standard size carbon adsorption vessel is a 20,000-lb carbon unit based on information provided by Mr. Wichman. Mr. Wichman indicated that vessels have a diameter of approximately 10 ft and height to 8 ft. Thus, to avoid hydraulic overload for the full-scale system (< 5.7 gal/minute/square foot), the full-scale design is based on the 20,000-lb carbon units.

Carbon treatment plant and associated costs

Table 18 summarizes the cost figures for the full-scale treatment plant. Details of the design and the cost estimates are provided as follows.

Table 18 Summary of Capital and Annual Operating Costs for Full-Scale Carbon Treatment Plant	
Plant Capital Costs	
Description	**Cost, $**
Concrete pad	13,414
Carbon adsorption units	427,205
Pumps	24,471
Piping	3,478
Electrical	765
Building (enclosure)	200,000
Captial cost total	669,333
Annual Operational and Maintenance Cost	
Labor and maintenance	24,200
Electrical	5,518
Backwash water	3,780
Carbon replacement	18,740
Subtotal (with carbon regeneration and reuse)	52,238/Year
Cost for virgin carbon	32,726
Carbon disposal	20,464
Subtotal (with virgin carbon replacement and disposal)	86,688/Year
Annual O & M cost total	86,688/Year

Plant layout and capital costs. As shown in Figure 31, the Omaha District design consists of four 20,000-lb carbon vessels placed on an uncovered concrete pad adjacent to Building 1383. Treated water will be collected in a sump after it passes through the existing air stripper and is pumped through the carbon beds. The water will pass through two sets of two absorbers operated in a parallel flow mode. Each set of absorbers consists of two 20,000-lb units 10 ft in diameter operated in series with down flow. The carbon-treated water will be returned to the existing secondary surge tank on the posttreatment side of the stripper tower. As an addition to the Omaha District design, it is also recommended by WES that a building be provided to protect the carbon units from the weather and to heat the associated piping. The estimated cost for the building and a small access road is $200,000. Details of the equipment are provided in Table 19, and the details of the cost estimate for the carbon system are provided in Appendix J.
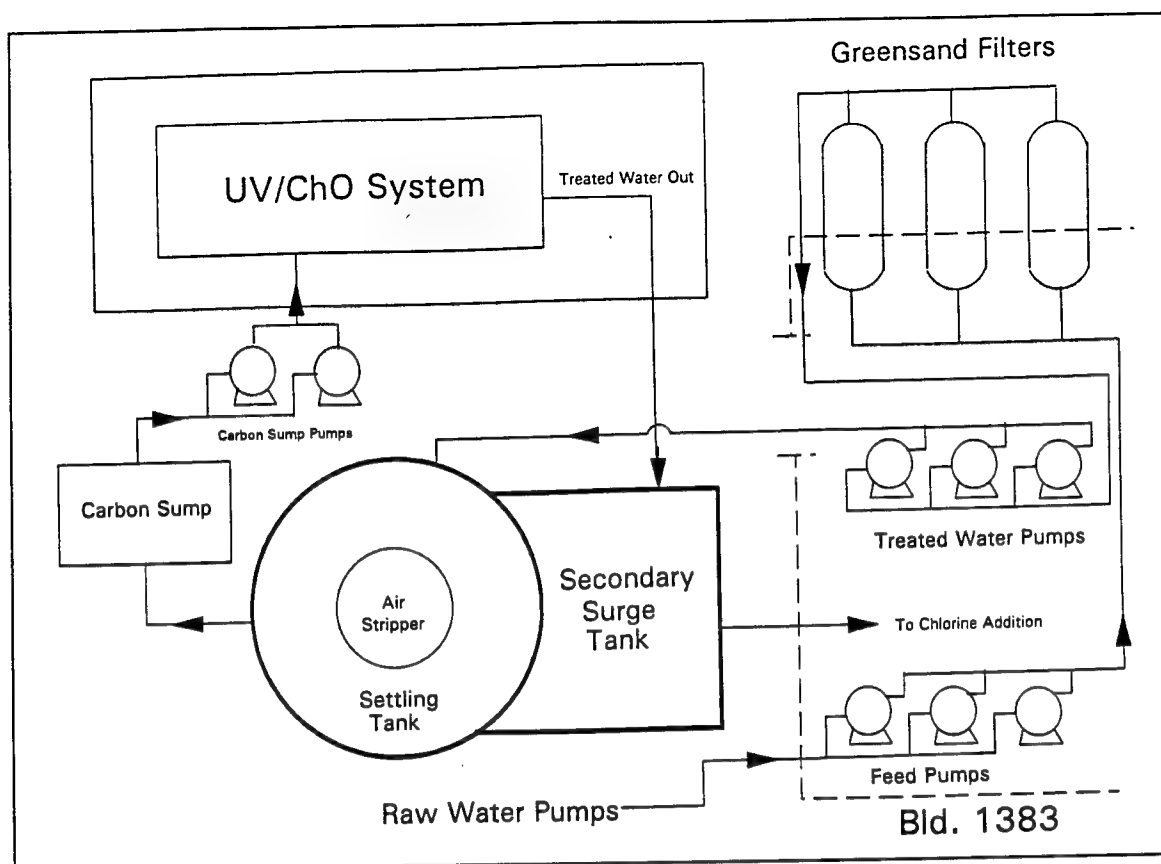
Figure 31. Proposed carbon adsorption treatment plant layout

Operation expenses. Based on a 20,000-lb absorber, a carbon utilization rate of 2.05 ft³ of dry carbon per 1 million gallons of water treated, and assuming the plant operates at full capacity of 1 MGD, a single absorber will provide 335 days of treatment prior to breakthrough (these calculations are shown in Appendix G).

The bulk price for F-200 carbon provided by Calgon is $0.83/lb of dry carbon.[1] This figure includes delivery, regeneration, and transfer. Using this unit cost for carbon and a carbon regeneration rate of 335 days, it is calculated that carbon cost will be $18,740/year if the carbon can be regenerated and reused. If the carbon must be disposed, virgin carbon (at a cost of $1.50/lb of dry carbon) will be required to refill the adsorption vessel at a cost of $32,726/year. Adding to this cost are the expenses associated with the disposal of the spent carbon estimated at $20,464/year (as shown in Appendix K).

In addition to carbon usage, additional annual costs would also be incurred. These include labor and maintenance, electrical, and water usage for carbon

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[1]   Personal Communication, 1993, Chuck Polinsky, Calgon Corporation, Houston, TX.

Table 19	
Details of Equipment for Full-Scale Carbon Treatment System	
Equipment	**Description**
Design capacity of plant	1 MGD
Carbon Units	
Number of units	4
Diameter of each unit	10 ft
Carbon capacity	20,000 lb of dry virgin carbon
Materials of construction	Carbon steel
Pumps	
Number	2
Type	Centrifugal
Capacity	700 GPM
Pumping head	48 ft of water
Piping	
Length	35 ft (linear)
Size	10 in.
Material	Carbon steel
Pad and Sump	
Pad size	30 by 30 by 1 ft
Pad material	Concrete
Sump size	10 by 10 by 10 ft
Sump material	Concrete

backwashing. Details of how these costs were calculated are provided in Appendix L and are summarized in Table 18.

UV/oxidation treatment plant and associated costs

As discussed in the Objective of Study section of this report, the purpose of this study was to evaluate the feasibility of using two technologies GAC and UV/chemical oxidation (UV/ChO) for the removal of RDX from the drinking water and to make a recommendation regarding the best technology for use. While the details of the UV/ChO investigation are presented in a separate report entitled "Ultraviolet/Chemical Oxidation Treatment of RDX-Contaminated Waters at the Picatinny Arsenal" (Fleming, Bricka, Bailey 1995), this section briefly describes the design configuration of the UV/ChO system and cost analysis details.

As in the design of the full-scale carbon treatment system, the Omaha District was also tasked by WES to assist in the design of the full-scale UV/ChO system. Mr. Ted Streckfuss was assigned to this project and provided the design. The designed was based on a design flow rate of 1 million gallons per day (MGD) and the pilot plant operation data presented in Table 20.

Table 20 UV/ChO Pilot Plant Operational Data	
Optimum water flow rate	5 gpm
Retention time	3.75
Influent air flow rate to the ozone generator	190 scfh
Ozone concentration in the influent air	0.5%

Operation configuration. Based on the results of the pilot study, two basic configurations of the UV/ChO system should be discussed. The first is a system where both UV and ozone are utilized to remove the contaminants. The second configuration that was considered is a system that only utilizes UV treatment. UV treatment provides a lower cost alternative to UV/ozone treatment, but the analysis of the effluent from the UV-treated waters indicates that many unidentified intermediate compounds are being formed during treatment. These intermediate compounds appear as unidentified peaks in the High Performance Liquid Chromatography (HPLC) spectra. The addition of ozone to the UV treatment removes most of the intermediate compounds (there are less unidentified HPLC peaks). Concerns regarding the toxicity of the unidentified peaks result in questions regarding whether both UV and ozone treatment are needed. This issue has not been resolved. If the intermediate compounds produced during UV treatment prove to be nontoxic, UV treatment will provide a cost-effective treatment. A summary of the estimates for both systems are provided in Tables 21 and 22, and details of cost estimates are provided as follows.

UV/ozone system. The reactor was sized based on ozone utilization and the detention time required for treatment. As presented in Table 20, the pilot test indicated that an inlet air flow of 190 standard cubic feet per hour (scfh) at an ozone concentration of 0.5 percent was optimal for RDX destruction. Using the 1 MGD design flow rate of the full-scale system, approximately 260 lb of ozone per day will be required for treatment. Thus, an ozone generator having a capacity of 300 lb/day should be appropriate. In addition, the detention time of 3.75 min in the pilot scale will require approximately 2,600 gal of retention volume in the full-scale system. Conversations with the Ultrox corporation indicate that an Ultrox model F-2600 UV/ozone unit should be appropriate for treatment.[1] The capital cost for the F-2600 including supervision, inspection, and overhead is $683,859. As shown in Figure 32, this system would be placed in an area adjacent to Building 1383 (the same location as indicated in Figure 31 for the carbon adsorption system). Unlike the carbon adsorption system, an enclosure for the UV/ChO system is a requirement not an option. The UV/ChO system must be protected from the

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[1] Personal Communication, 1992 and 1993, J. Zeff, Ultrox Corporation, Santa Ana, CA.

Table 21
Summary of Captial and Annual Operating Expenses for Full-Scale UV/Ozone Treatment Plant

Plant Capital Costs	
Description	**Cost, $**
Concrete pad	13,414
Feed pumps	24,471
Piping	3,478
Electrical	15,765
UV/ozone system (including): 　a. Ozone generator 　b. Air preparation system 　c. Air compressors 　d. UV reaction vessel and lamps 　e. Ozone destruction unit with catalyst beds	683,859
Building (enclosure)	200,000
Captial cost total	940,987
Annual Operational and Maintenance Cost	
Labor and maintenance	17,377
Electrical 　UV 　Ozone generation 　Pumping	 10,910 55,662 5,518
Total O & M annual expenses	89,467

Table 22
Summary of Capital and Annual Operating Expenses for Full-Scale UV-Only Treatment Plant

Plant Capital Costs	
Description	**Cost, $**
Concrete pad	13,414
Feed pumps	24,471
Piping	3,478
Electrical	5,765
UV/ozone system (including UV reaction vessel and lamps)	341,930
Building (enclosure)	200,000
Capital cost total	589,058
Annual Operational and Maintenance Cost	
Labor and maintenance	17,377
Electrical 　UV 　Ozone generation 　Pumping	 10,910 0 5,518
Total O & M annual expenses	33,805
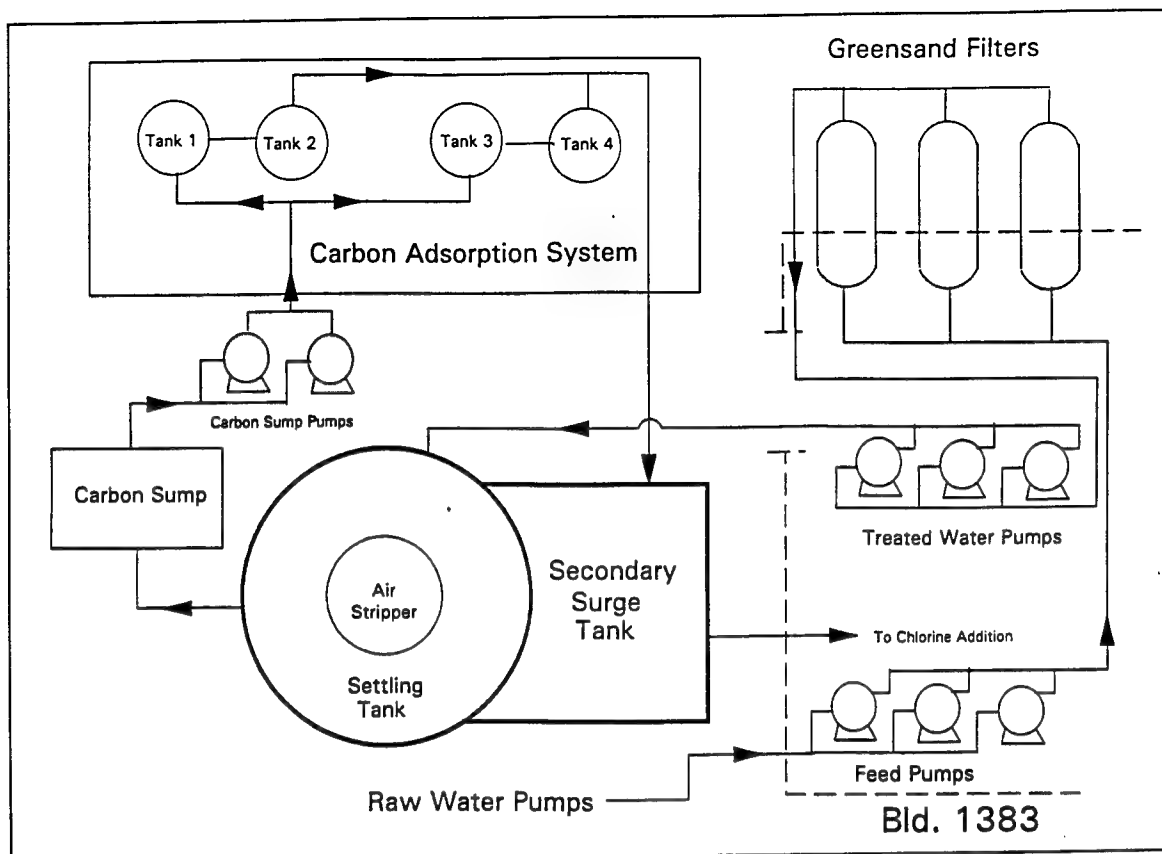
Figure 32. Proposed UV/ChO treatment plant layout

weather. Details of the capital cost-estimating procedures for the UV/ChO systems are presented in Appendix L.

The operation costs for this system are based on an estimate provided by the Ultrox Corporation of $0.23/1,000 gal of water treated.[1] Electrical consumption accounts for 79.3 percent of the total cost with the remainder attributed to equipment maintenance and lamp replacement. Approximately 65 percent of the total operation costs can be attributed to electrical power to generate ozone and 13 percent for UV treatment. Using this information, the total annual operation and maintenance (O&M) cost for the UV/ozone system is estimated at $89,467. Details of the operational cost-estimation procedures are presented in Appendix L.

UV system without ozone. By reducing the requirement for ozone, the capital and operational costs for RDX destruction are significantly reduced. Equipment requirements for this system are similar to that for the UV/ozone system. The reactor volume and UV requirements will remain the same as well as the UV requirement. By eliminating the requirement for ozone, the reactor capital costs are reduced by half to 341,930. All other requirements

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[1] Personal Communication, 1992 and 1993, J. Zeff, Ultrox Corporation, Santa Ana, CA.

remain the same except for capital layout for the electrical support. Because there is a substantial reduction in the requirement for electrical power, estimated costs for the capital expenditures for electrical support associated with the UV-only system are estimated at $5,757. Total capital layout for this UV-only system is estimated at $589,058; this is more than a 37-percent reduction over the UV/ozone system.

Annual operating costs are also reduced because of a reduced electrical power consumption. The ozone generator requires $55,662/year of electrical power. By eliminating the ozone generator, the total estimated annual O&M costs are reduced to $33,814. Details of the capital and O&M cost estimates for the UV-only system are also provided in Appendix M.

Comparison of UV/ChO and Carbon Treatment

Table 23 summarizes the capital and O&M costs associated with the four systems under consideration in this study (carbon adsorption with and without regeneration, UV with ozone, and UV only). Of these systems, the UV-only system appears to be the most cost-effective. The major problem associated with this design is the additional risk associated with the generation of intermediate compounds (unidentified HPLC peaks) as a result of the breakdown of the RDX. While attempts have been made to identify these peaks, these efforts have been unsuccessful to date. These peaks may represent the formation of harmless compounds, but they may also indicate the formation of compounds more toxic than the original contaminant RDX. While, intermediate identification is outside the scope of this study, intermediate identification as well as destruction pathway research will continue under a separately funded program at WES.

Table 23 Expenditure Comparison Table of Carbon Adsorption and UV/ChO Systems				
	Carbon (no regeneration)	Carbon (regeneration)	UV/Ozone	UV Only
Captial Costs	669,333	669,333	940,987	589,058
Annual O&M Costs	86,688	52,538	89,467	33,814

At this time, a carbon adsorption system is recommended to treat the RDX-contaminated drinking water. This recommendation is based on the fact that carbon adsorption is a mature technology and is a proven technology for the treatment of RDX-contaminated wastewater. The disposal of carbon may be required during the initial operation of the treatment system, but the RDX buildup on the carbon should be well below any reactive limits. The regeneration of the spent carbon should be investigated and is a likely possibility resulting in a substantial reduction in operational cost.

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On the other hand, if the results of the intermediate identification and pathway research is successful and timely, and the intermediates prove to be non-toxic, the UV-only system should be considered for implementation.

4   Conclusions and Recommendations

Conclusions

While there were many objectives for this investigation, the main objective was to determine if GAC and/or UV/ChO technologies can be utilized to remove the concentration of RDX in drinking water at Picatinny Arsenal to levels less than 1 ppb; if both technologies prove to be effective, the objective was to recommend one of these technologies. Based on the results presented in this report, the following conclusions are presented.

a. Both the GAC and UV/ChO technologies proved to be successful in removing the required concentration of RDX. Since the UV/ChO treatment generated unidentified intermediates that may pose health risks, a GAC treatment system is recommended over the UV/ChO system for the treatment of drinking water at Picatinny Arsenal. GAC provides a cost-effective method of RDX removal to meet current and future health advisory limits. However, if future studies indicate that the intermediates generated during UV/ChO treatments pose no health risks, this treatment could be used and may provide a more cost-effective method than the GAC treatment.

b. Many GAC types were screened for their potential usefulness for the treatment of RDX and HMX. Five carbons were selected for laboratory study based on the criteria of surface area, pore volume, iodine number, mean particle diameter, carbon base material, and historical explosive treatment. The five carbons selected were Westates' CC-601, Calgon's Filtrasorb-200 and Filtrasorb-400, and American Norit's Hydrodarco-4000 and ROW 0.8. These carbons were effective in removing RDX and HMX from the drinking water from Well 410 at Picatinny Arsenal.

c. Calgon's Filtrasorb-200 and American Norit's Hydrodarco-4000 were identified as effective carbons for the treatment of RDX and HMX from the drinking water from Well 410 at Picatinny Arsenal. Both

carbons can be utilized to meet the performance criteria of 1 ppb RDX in the treated effluent.

d. In both the isotherm studies and pilot column studies, the adsorption capacities of F-200 and H-4000 carbons are high.

e. The recommended GAC treatment system layout is provided in Figure 32, and equipment details are provided in Table 20.

In addition, the following design information is provided:

Absorber life   335 days

F-200 carbon utilization rate 2.05 ft^3 of dry carbon per
                                       1 million gallons

H-4000 carbon utilization rate 1.99 ft^3 of dry carbon per
                                       1 million gallons

Optimal EBCT for the F-200   3.38 min

Recommendations

If innovative technologies such as UV/ChO and biological remediation are used for explosive destruction, additional research must be conducted. Studies need to address the identification of intermediate products formed during destruction reactions. Also such research should be directed towards identifying reaction breakdown pathways.

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Appendix A
Properties of RDX and HMX
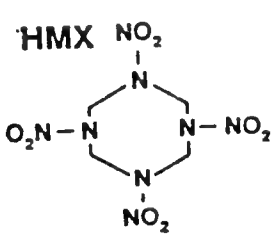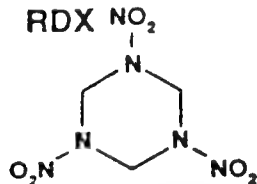
Table A1 Chemical and Physical Properties of RDX	
CAS No.	121-82-4
Synonyms	Cyclonite/hexogen Chclotrimethylenetrinitramine Hexahydro-1,3,5-trinitro-1,3,5-triazine RDX sym-Trimethylenetrinitramine T_4 1,3,5-trinitrohexahydro-s-trianzine
Molecular Weight	222.26
Empirical Formula	$C_3H_6N_6O_6$
Structure	
Physical State	White crystalline solid-orthorhombic crystal
Specific Gravity	1.816 @ 20 °C
Melting Point	204.1 °C
Heat of Combustion	2,259.4 cal/g
	(Continued)

Table A1 (Concluded)

Solubility Characteristics	
Water	0.00076% w/v @ 25 °C (7.6 mg/ℓ) to 42.3 mg/ℓ (20 °C) reported
Cyclohexanone	12.7% w/w @ 25 °C
Cyclopentone	9.9% w/w @ 25 °C
Acetone	8.3% w/w @ 25 °C
Nitrobenzene	1.5% w/w @ 25 °C
Methylisobutenyl Ketone	3.0% w/w @ 25 °C
Methylacetate	1.9% w/w @ 20 °C
Acetic anhydride	4.9% w/v @ 30 °C
Henry's Law Constant	2×10^{-3} torr m^{-3}
log Kow	0.86
log Koc	2.00
Vapor Pressure	4.03×10^{-09} torr (25 °C)
Auto Ignition Temperature	197 °C

Note: Source - Adapted from Sullivan et al. (1979);[1] McLellan, Hartley, and Brower (1988a); and the Hazardous Component Safety Data Sheet.

Table A2
Chemical and Physical Properties of HMX

CAS No.	2691-41-0
Synonyms	Cyclotetramethylenetetranitramine HMX Octahydro-1,3,5,7-tetranitroazocine Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine Octogen RRI 1,3,5,7-tetranitro-1,3,5,7-tetraazocyclooctane
Molecular Weight	296.16
Empirical Formula	$C_4H_8N_8O_8$
Structure	RDX
Physical State	Colorless, crystalline solid, four polymorphic forms, beta from least sensitive and most stable
Specific Gravity	1.87 (beta form)

(Continued)

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[1] References cited in this appendix are located at the end of the main text.

Table A2 (Concluded)

Melting Point	276 to 280 °C
Vapor Pressure	3×10^{-9} mmHg @ 100 °C

Solubility Characteristics
  Water, mg/ℓ
 	
  Acetone, mg/ℓ
  Cyclohexanone, mg/ℓ
  Acetic anhydride, mg/ℓ
  Dimethyl sulfoxide, g/100 g
	
	1.14 (5 °C)
	4.42 (10 °C)
	6.63 (20 °C)
	11.56 (30 °C)
	17.43 (35 °C)
	140 (83 °C)
	2,200 (30 °C)
	5,300 (30 °C)
	1,300 (30 °C)
	57 (30 °C)

Henry's Law Constant	2.60×10^{-15} (atom m^{-3} mole^{-1})
log Kow log Koc	0.26 0.54
Vapor Pressure	3.33×10^{-09} torr (25 °C)
Auto Ignition Temperature	234 °C

Note: Source - Adapted from Kitchens and Brownlee (1979); McLellan, Hartley, and Brower (1988b); and the Hazardous Component Safety Data Sheet.

Appendix B
Manufacturers Product Bulletins for Carbon Used in This Study

N HYDRODARCO®

NORIT

AMERICAN NORIT COMPANY, INC.

ACTIVATED CARBON

HYDRODARCO® 4000
GRANULAR ACTIVATED CARBON

This granular activated carbon is designed for water treating applications. It is produced by high temperature steam activation of lignite coal. HYDRODARCO 4000 has a wide pore size distribution and large pore volume. These characteristics provide HYDRODARCO 4000 with rapid adsorption rate and high capacity for dissolved organics.

Potable Water

HYDRODARCO 4000 adsorbs taste, odor, color and toxic organic compounds from drinking water. It has the highest capacity of any commercial water carbon for tannic and humic compounds which are precursors for trihalomethane (THM) formation. HYDRODARCO 4000 effectively removes pesticides, herbicides, synthetic organic chemicals and many other suspected carcinogenic compounds which may find their way into water supplies. HYDRODARCO 4000 meets all AWWA B-604 standards for activated carbon for rapid gravity filters and pressure contactors used in potable water purification systems.

Wastewater and Contaminated Groundwater

Whether applied at point source or in a polishing filter, HYDRODARCO 4000 can be used to meet discharge limits for most regulated organics. The broad pore size distribution of HYDRODARCO 4000 allows treatment of complex wastewater streams containing large and small molecular pollutants. The macroporous structure of HYDRODARCO 4000 provides high tolerance for naturally occurring material (NOM) which interferes with adsorption of organic contaminants from groundwater.

Typical Properties

Tannin value, ppm	220
Molasses number	450
Molasses decolorizing efficiency	95
Iodine number	600
Total surface area (N_2 BET method), m^2/g	625
Mean pore radius, Å	29
Total pore volume, ml/g	0.93
pH	5.0
Apparent density, vibrating feed, g/ml	0.40
Particle density, wetted in water, g/ml	1.4
Bed density, backwashed and drained, lbs/cu. ft.	24
Poured apparent density, lbs/cu.ft.	22
Voids in packed bed, %	50

(continued on reverse side)

NSF.

B2

	Specifications	Typical Value
Sieve analysis (U.S. Sieve Series)		
+ 12 mesh, %	5 max.	2
− 40 mesh, %	5 max.	2
Mean particle diameter, mm	0.9-1.1	1.00
Effective size, mm	0.65-0.8	0.72
Uniformity Coefficient	1.9	1.6
Abrasion Number, (NBS method),	70 min.	80
Moisture, %	8 max.	6
Dust, %	0.3 max.	0.15

PRESSURE DROP CURVE
FOR HYDRODARCO 4000
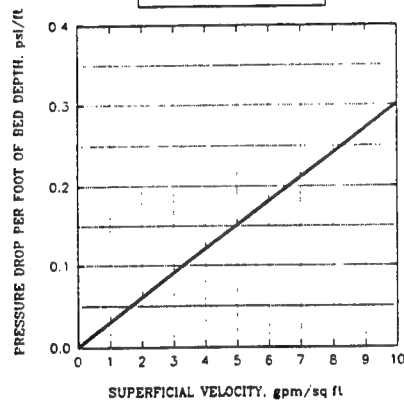
BED EXPANSION CURVE
FOR HYDRODARCO 4000
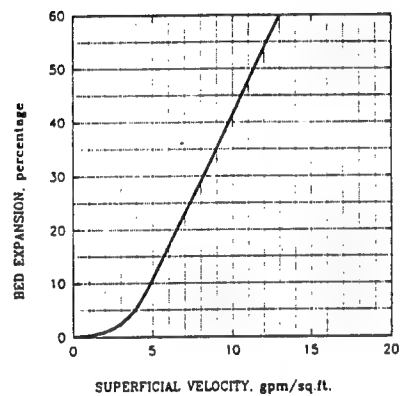
Packing and Shipping

HYDRODARCO 4000 is available in 40 lb. bags, 30 bags per pallet, shrink-wrapped with a net pallet weight of 1200 lbs. It is also available in bulk trucks and semi-bulk containers consisting of 880 lbs. bulk propylene bags or 1000 lb. bulk corrugated boxes.

Safety

CAUTION, avoid inhalation of excessive carbon dusts. No problems are known to be associated in handling this material. However, dust may contain silica (quartz). Long term inhalation of high dust concentrations can lead to respiratory impairment. Use forced ventilation or a dust mask when necessary for protection against airborne dust exposure (see Code of Federal Regulations-Title 29, Subpart Z, par. 1910.1000 Table Z-3).

AQUA-Carb™

Water Treatment Carbons

DESCRIPTION

Westates' AQUA-CARB™ activated carbons are high performance adsorbants specifically designed for water treatment. Manufactured from unique high quality substrates, AQUA-CARB activated carbons feature internal pore structures that are ideally suited to remove organic compounds from water. High removal efficiency coupled with their very low water soluble ash content make AQUA-CARB activated carbons the best value for your water treatment needs.

QUALITY CERTIFIED

The process for manufacturing activated carbons involves procedures with many variables that require strict quality control. Westates maintains a modern ASTM quality control laboratory to certify that Westates products meet or exceed all required specifications.
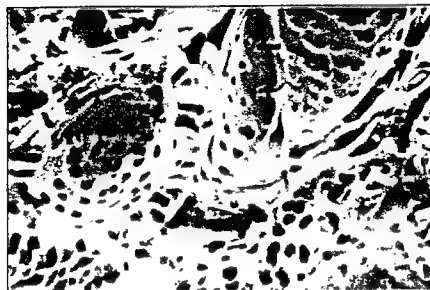
Coconut Shell at 2.2kx mag.

SAFETY

Wet activated carbon readily adsorbs atmospheric oxygen. Dangerously low oxygen levels may exist in closed vessels or poorly ventilated storage areas. Workers should follow all applicable state and federal safety guidelines for entering oxygen depleted areas.
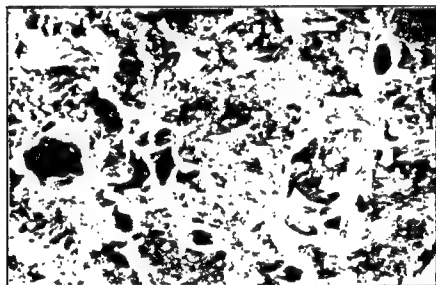
Bituminous Coal at 250x mag.

WESTATES CAPABILITIES

Westates has the facilities for manufacturing, regenerating and characterizing activated carbon. Selected high quality carbons are also available from other sources giving Westates the capability of supplying the best carbon for your treatment needs. We have more than 20 years experience in the design of activated carbon adsorption systems. Our technical staff provides expert guidance in selecting the right system for your needs. Our laboratory is fully equipped to provide complete quality control and a continuing analysis of your carbon to maintain maximum efficiency.

All information presented here is believed to be reliable and in accordance with accepted engineering practice. However, Westates makes no warranties as to the completeness of the information. Users should evaluate the suitability of each product to their own particular application. In no case will Westates be liable for any special, indirect, or consequential damages arising from the sale, resale, or misuse of its products.

SPECIFICATIONS	CO-401	KP-401	CC-601	CC-401
Size (U.S. Sieve)	8 x 30	–	12 x 40	12 x 30
Iodine No. (Min)	900	850	1100	900
Hardness No. (Min)	97	92	99	99
Abrasion No. (Min)	76	76	99	99
Moisture (Max)	2%	2%	2%	2%
Mean Particle Diam.	1.45mm	1.9mm	1.1mm	1.2mm
Shape	Granule	Pellet	Granule	Granule
Ph Water Extract	7.5	7.5	9.5	9.5
Soluble Phosphate	N.D.*	N.D	N.D	N.D
Ash (Water Soluble)	< 1%	1%	1%	1%
Apparent Density (g/cc)	.49		.49	.52
(lb/ft³)	30.5	30.5	30.5	32

(Refer to selection guide on reverse)

*Non-Detectable

WESTATES carbon
ACTIVATED CARBON SYSTEMS

WESTATES CARBON, INC
2130 Leo Ave , Los Angeles, CA 90040
PHONE (213) 722 7500
FAX (213) 722-8207 TWX 910 321 2355

AQUA-Carb™
— SELECTION GUIDE —

APPLICATIONS

• Potable Water

• Beverage Manufacturing

• Wastewater Treatment

• Process Water Recycling

CO-401
Broad spectrum granular adsorbant designed for removal of organics in most water applications. A general all purpose product manufactured from bituminous coal.

KP-401
Broad spectrum adsorbant with uniform particle characteristics designed for use when flow characteristics are important or when very low dust content is required, such as for food processing. A pelletized product manufactured from bituminous coal.

PRESSURE DROP

CC-601
CC-401
(12 x 30)

CO-401 (8 x 30)
KP-401

PRESSURE DROP (in H₂O/bed ft.)

FLOW (gpm/ft²)

CARBON BED EXPANSION

(1) CC-601 and CC-401 (12 x 30)
(2) CO-401 (8 x 30)
(3) KP-401

% BED EXPANSION

BACKWASH FLOW (gpm/ft²)
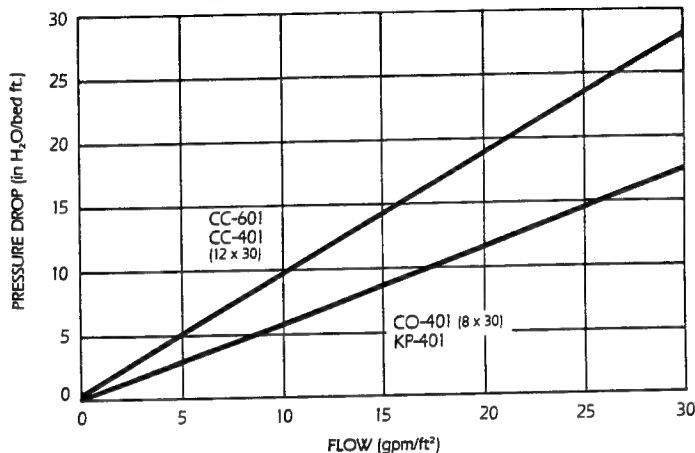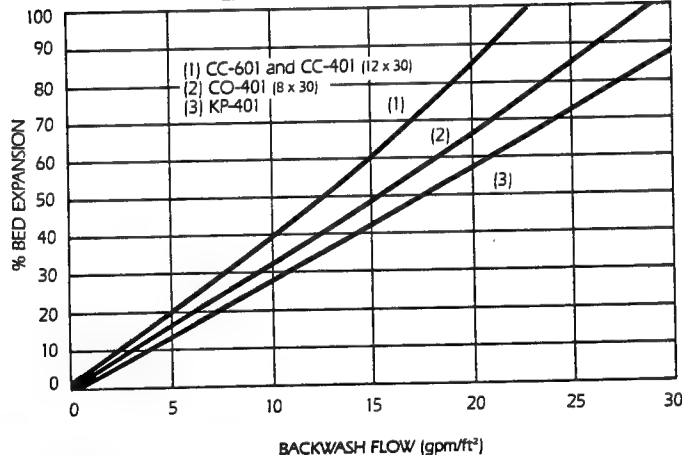
APPLICATIONS

• Potable water chlorine and chloramine removal

• TCE, PCE removal

• Plating solution clarification

• Process water organic scavenging

CC-601
A high-capacity adsorbant manufactured from coconut shell and for removal of small molecular size VOCs (TCE, PCE, etc.). The high hardness characteristics also significantly reduce attrition during handling.

CC-401
Similar to CC-601, except that it has slightly lower capacity. Used mainly where particle hardness is important.

WESTATES carbon

ACTIVATED
CARBON
SYSTEMS

WESTATES CARBON, INC.
2130 Leo Ave., Los Angeles, CA 90040
PHONE. (213) 722-7500
FAX. (213) 722-8207 TWX: 910-321-2355

NORIT

NORIT® ACTIVATED CARBON

PRODUCT INFORMATION
Bulletin No. 220
Revised 8-90

NORIT ROW 0.8
GRANULAR ACTIVATED CARBON

Supplied as an 0.08 mm extrudate, this carbon is designed for water and waste treatment and for other liquid phase adsorption systems requiring high resistance to abrasion.

Typical Analysis:

Apparent density, - g/ml	.400
- lbs./ft.^{3} (approx.)	24.8
Density, backwashed/drained, g/ml	.360 $= 22.5 \frac{lb}{ft^3}$
Moisture, %, as packed	2.0
Ash, %	6.0
Phenol adsorption, %	6.0
Iodine ads., mg/g	1000
Dechlorination half-value, cm	5.0
Hardness (ASTM)	92
Total pore volume, ml/g	1.0
Pellet diameter, mm	0.8

Packaging

40 x 44.1 lb. net bags (71.0^3 ft.) pallet, shrinkwrapped. Net pallet weight is 1764 lbs. Orders less than palletload are supplied in bags plus shipping cartons without palletizing.

DOWNFLOW PRESSURE DROP

PRESSURE DROP (In. Water per Ft. of Bed Depth) vs. SUPERFICIAL VELOCITY (GPM per Sq. Ft.)

Water 68 °F

UPFLOW BED EXPANSION

BED EXPANSION (%) vs. BACKWASH RATE (GPM per Sq. Ft.)

Water 68 °F
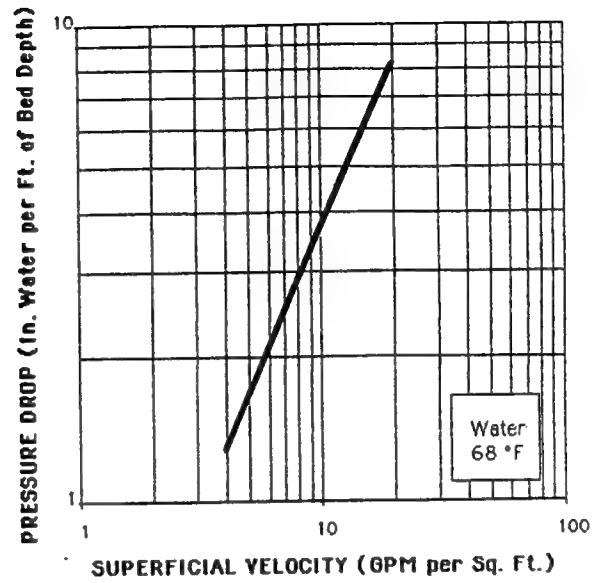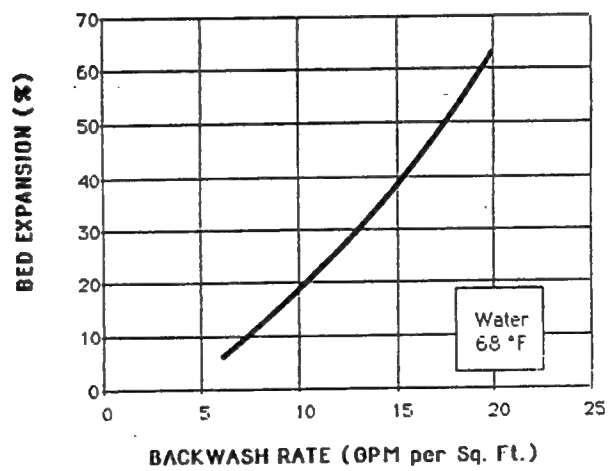
FILTRASORB® 200 GRANULAR ACTIVATED CARBON FOR WATER TREATMENT

ACTIVATED CARBON PRODUCT BULLETIN

CALGON
CALGON CARBON CORPORATION

DESCRIPTION

Filtrasorb 200 is a grade of granular activated carbon manufactured by Calgon Carbon Corporation for removal of dissolved organic material from municipal and industrial water supplies. It is manufactured from select grades of bituminous coal to produce a high-density, durable granular product capable of withstanding the abrasion and dynamics associated with repeated reactivation, hydraulic transport, backwashing and mechanical handling. Activation is carefully controlled to produce exceptionally high internal surface area with optimum pore size for adsorption of a broad range of high and low molecular weight impurities.

PURPOSE

Filtrasorb carbon performs a dual function by filtering out turbidity and adsorbing dissolved organic materials such as insecticides, detergents, phenols and other contaminants from both natural and industrial sources which cause taste, odor and color problems.

Filtrasorb carbon can be used to upgrade water quality using existing rapid sand filtration equipment. Used as a complete replacement for sand or coal, it functions as a dual purpose medium: providing both filtration and adsorption. As a partial replacement for filter media, it can be used as an adsorbent to complement normal filtration processes. In either case, conversion to Filtrasorb imposes no changes to a plant's normal filtration operations.

Very large water treatment plants, or plants confronted with exceptionally high contaminant loading, may wish to investigate the economic feasibility of carbon reactivation. In most municipal and industrial water supply treatment applications, however, operating experience indicates that life of the original carbon bed ranges from 3 to 5 years and reactivation is not employed.

ADVANTAGES

- No dust—clean process
- Less handling—once Filtrasorb carbon is placed in the filter bed it requires no further handling until replacement
- Reserve capacity of activated carbon eliminates need for operating adjustments as raw water quality fluctuates
- Reactivation and reuse of granular carbon reduces treatment costs
- Improves water quality, taste, odor and appearance
- Reserve capacity provides safety margin against undetected organic pollutants and accidental spills of toxic organic materials

PHYSICAL PROPERTIES

Total surface area, N_2 BET method (m²/g)..............................850-900
Bed density backwashed and drained (lbs/ft³*)......................29 approx
Particle density wetted in water (g/cc)...................................1.4-1.5

to be used to calculate volume requirements
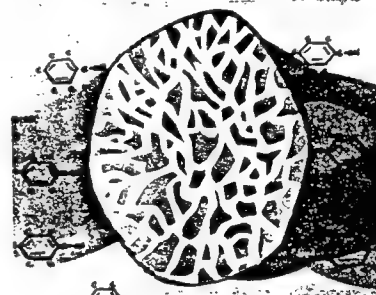
The top rendering is a cross section of a granular activated carbon particle showing the intricate pore structure which significantly adds to the total surface area.

The middle drawing shows water containing phenolic molecules being exposed to the carbon granule.

The bottom rendering represents the phenolic impurities removed from the water and adsorbed in the intricate pore structure of the carbon (Average diameter of actual pore is 0.2 millionth of an inch.)

Bulletin 27-74c

SPECIFICATIONS

	Specifications	Typical Analysis
Sieve Size U.S. Std. Series		
Larger than No.12 (max %)	5	1
Smaller than No. 40 (max %)	4	2
Effective size (mm)	0.55-0.75	0.6
Iodine Number (min)	850	900
Abrasion Number (min)	75	80
Moisture as packed (max %)	2	0.5
Ash (max %)	—	5-8
Water Soluble Ash (max %)	—	0.5
Percent Phosphate (as delivered) Max.	—	0.1

PACKAGING

Filtrasorb is packaged in five-ply kraft bags (55 lbs net, 56 lbs gross). For less than one-ton quantities, each bag is packaged in a protective shipping carton—Tare weight of carton—2 lbs. Available on 48″ X 48″ trailer-truck pallets, maximum 40 bags per pallet — 20 pallets maximum for standard 40-foot trailer. Bulk shipments by truck 20,000 lbs minimum; and by rail 50,000 lbs minimum.

CAUTION

Wet activated carbon preferentially removes oxygen from air. In closed or partially closed containers and vessels, oxygen depletion may reach hazardous levels. If workers are to enter a vessel containing carbon, appropriate sampling and work procedures for potentially low-oxygen spaces should be followed, including all applicable Federal and State requirements.

FILTRASORB 200
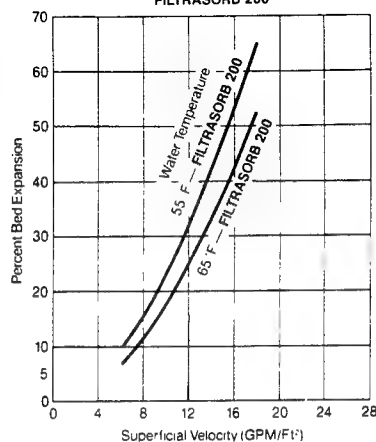
DOWNFLOW PRESSURE DROP THROUGH A BACKWASHED SEGREGATED BED OF FILTRASORB 200
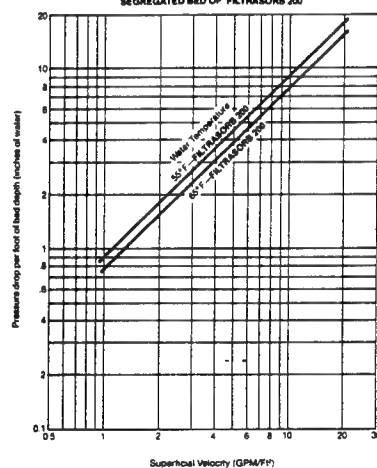
Printed in U.S.A.

FILTRASORB® 300 and 400 GRANULAR ACTIVATED CARBONS FOR POTABLE WATER TREATMENT

CALGON — CALGON CARBON CORPORATION

ACTIVATED CARBON PRODUCT BULLETIN

TWO GRADES OF HIGH-ACTIVITY GRANULAR ACTIVATED CARBON WHICH PROVIDE THE MOST COST EFFECTIVE REMOVAL OF TASTE, ODOR AND DISSOLVED ORGANIC COMPOUNDS FROM PUBLIC WATER SYSTEMS.

DESCRIPTION

Filtrasorb 300 and Filtrasorb 400 are two high activity granular activated carbons developed by Calgon Carbon Corporation for the removal of tastes, odors, and synthetic organic contaminants from public water supplies.

Both activated carbons are manufactured from select grades of bituminous coal to produce a high-activity, durable granular product capable of withstanding the abrasion associated with repeated backwashing, air scouring, and hydraulic transport. Activation is carefully controlled to produce exceptionally high internal surface area with optimum pore size for effective adsorption of a broad range of high and low molecular weight organic contaminants.

PURPOSE

Filtrasorb activated carbons can be used to upgrade water quality in existing sand filtation systems. Used as a complete replacement for sand or anthracite coal, Filtrasorb activated carbons function as a dual purpose medium, providing both filtration and adsorption. As a replacement for existing filter media, Filtrasorb activated carbon can be used as an adsorbent to complement normal filtration processes. In either case, conversion to Filtrasorb activated carbon imposes no major changes to a plant's normal filtration operations.

In situations where average flow volume is so high that complete replacement of existing media does not provide sufficient contact time with the activated carbon, Calgon Carbon Corporation can provide complete modular adsorption systems as an add-on treatment stage. These systems provide a rapid, effective and economical method of upgrading water quality to meet the 1986 Safe Drinking Water Act Amendments (SDWA), or to solve taste and odor problems.

Hydraulic installation makes filling gravity filter beds with Filtrasorb granular activated carbon a simple and clean operation.

ADVANTAGES

• **Proven Reliabilty** — Years of experience in more than 150 public water supply systems have established granular activated carbon adsorption as the most reliable taste and odor removal process available.

• **Reserve Capacity** — The reserve capacity of granular activated carbon can effectively control sudden water quality fluctuations and unexpected contamination. There are no messy adjustments of powdered carbon feed systems or problems of undertreatment or wasteful overtreatment.

• **Low Cost** — In plants using 2-4 ppm powdered activated carbon feed on a year-round basis, granular activated carbon filter beds are more economical.

• **Easy to Use** — Installation of granular activated carbon is a simple and clean operation. In use, it needs no more handling than conventional sand filter media—no bags of dusty powdered activated carbon to handle every day.

Bulletin 20-68f

SPECIFICATIONS

	FILTRASORB 300		FILTRASORB 400	
	Specification Value	Typical Analysis	Specification Value	Typical Analysis
U.S. Standard Series Sieve Size				
Larger than No. 8	Max. 15%	8	—	—
Smaller than No. 30	Max. 4%	2	—	—
Larger than No. 12	—	—	Max. 5%	1
Smaller than No. 40	—	—	Max. 4%	2
Iodine Number, min.	900	970	1000	1050
Abrasion Number, min.	75	80	75	78
Moisture (max.)	2.0%	0.8%	2.0%	0.9%

PHYSICAL PROPERTIES

	FILTRASORB	
	300	400
Total surface area (N$_2$, BET method) m^2/g*	900-1000	900-1100
Bulk density, lbs/ft^3**	28	27
Pore volume, cc/g*	0.75-0.85	0.85-0.95
Effective size, mm	0.8-1.0	0.55-0.75
Uniformity coefficient (max.)	2.1	1.9

*For general information and not to be used as purchase specifications.

**Used to calculate volume requirements.

PACKAGING

Filtrasorb activated carbon can be supplied in 55-lb net wt. multi-wall bags, 1000-lb net wt. super sacks, or shipped by bulk truck.

CAUTION

Wet activated carbon preferentially removes oxygen from air. In closed or partially closed containers and vessels, oxygen depletion may reach hazardous levels. If workers are to enter a vessel containing carbon, appropriate sampling and work procedures for potentially low-oxygen spaces should be followed, including applicable federal and state requirements.

HEAD LOSS CHARACTERISTICS
PRESSURE DROP CURVES
FILTRASORB 300 AND FILTRASORB 400
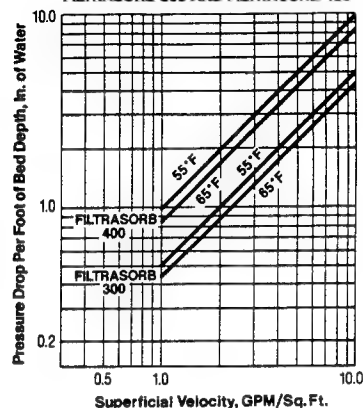
FILTRASORB 300 AND FILTRASORB 400
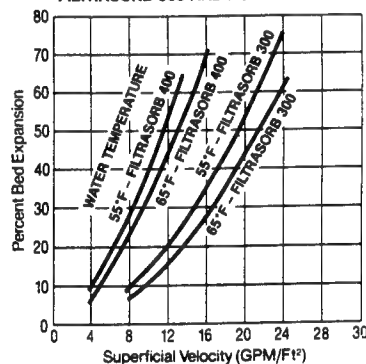
For additional information, contact Calgon Carbon Corporation,
P.O. Box 717, Pittsburgh, Pennsylvania 15230-0717
Phone (412) 787-6700

CALGON

CALGON CARBON CORPORATION

Printed in U.S.A.

Appendix C
Analytical and Quality Control Results for Isotherm Studies

Table C1
Carbon Isotherm Study Raw Chemical Analysis

Carbon Type: Calgon F-200

Carbon Dosage mg/l	Lot #	Rep	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
0	EDF	1	<0.388	<0.270	<0.767	<1.16	<1.11	1.670	<1.54	5.89	<0.191
0	EDF	2	<0.388	<0.270	<0.767	<1.16	<1.11	1.570	<1.54	5.69	<0.191
0	EDF	3	<0.388	<0.270	<0.767	<1.16	<1.11	1.620	<1.54	5.75	<0.191
10	EDF	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	EDG	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	EDG	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	EDG	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	EDG	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	EDG	3	<0.388	0.286	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDG	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDG	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDG	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDG	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDG	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDG	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	EDG	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	EDG	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	EDG	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDG	1	<0.388	0.328	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDG	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDH	3	0.912	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191

(Sheet 1 of 6)

Appendix C   Analytical and Quality Control Results

Carbon Type: Calgon F-400

Carbon Dosage mg/ℓ	Lot #	Rep	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
0	ECY	1	<0.388	<0.270	<0.767	<1.16	<1.11	1.860	<1.54	6.08	<0.191
0	ECY	2	<0.388	<0.270	<0.767	<1.16	<1.11	1.850	<1.54	6.06	<0.191
0	ECY	3	<0.388	<0.270	<0.767	<1.16	<1.11	1.940	<1.54	5.98	<0.191
10	ECY	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	ECY	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	ECY	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	ECZ	1	<0.388	3.770	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	ECY	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	ECZ	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	ECY	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	ECY	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	ECZ	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	ECY	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	ECY	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	ECZ	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	ECY	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	ECY	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	ECZ	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	ECY	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	ECY	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	ECY	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191

(Sheet 2 of 6)

Table C1 (Continued)

Carbon Type: Calgon F-400 pH 4.0

Carbon Dosage mg/ℓ	Lot #	Rep	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
0	EDD	1	<0.388	<0.270	<0.767	<1.16	<1.11	1.610	<1.54	5.58	<0.191
0	EDE	2	<0.388	<0.270	<0.767	<1.16	<1.11	1.680	<1.54	5.53	<0.191
0	EDE	3	<0.388	<0.270	<0.767	<1.16	<1.11	1.590	<1.54	5.26	<0.191
10	EDE	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	EDE	2	0.425	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	EDE	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	EDE	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	EDE	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	EDE	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDE	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDE	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDD	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDD	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDD	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDD	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	EDD	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	EDH	2	2.17	<0.486	<1.38	<2.09	<2.00	<1.560	<2.77	<1.11	<0.344
5,000	EDD	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDD	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDD	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDD	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191

(Sheet 3 of 6)

Appendix C   Analytical and Quality Control Results

Table C1 (Continued)

Carbon Type: Westates CC-601

Carbon Dosage mg/ℓ	Lot #	Rep	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
0	EDB	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	4.62	<0.191
0	EDB	2	<0.388	<0.270	<0.767	<1.16	<1.11	1.570	<1.54	5.74	<0.191
0	EDB	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	3.22	<0.191
10	EDA	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	EDB	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	EDB	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	EDB	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	EDB	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	EDB	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDB	1	<0.388	<0.270	1.86	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDB	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDB	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDA	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDB	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDA	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	EDB	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	EDB	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	EDA	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDB	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDB	2	<0.388	<0.270	1.65	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDA	3	<0.388	<0.270	1.08	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191

Appendix C   Analytical and Quality Control Results

Table C1 (Continued)

Carbon Type: Norit Row 0.8

Carbon Dosage mg/l	Lot #	Rep	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
0	ECZ	1	<0.388	0.650	0.986	<1.16	<1.11	1.540	<1.54	6.1	<0.191
0	ECZ	2	<0.388	0.483	<0.767	<1.16	<1.11	1.410	<1.54	5.94	<0.191
0	ECZ	3	<0.388	0.438	<0.767	<1.16	<1.11	1.180	<1.54	5.31	<0.191
10	ECZ	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	ECZ	2	<0.388	0.514	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	ECZ	3	<0.388	0.537	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	ECZ	1	<0.388	0.379	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	ECZ	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	ECZ	3	<0.388	0.328	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDA	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.458
500	EDH	2	1.91	<0.648	<1.84	<2.78	<2.66	<2.090	<3.70	<1.48	<0.191
500	EDA	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDA	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDA	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDH	3	4.04	<0.648	<1.84	<2.78	<2.66	<2.090	<3.70	<1.48	<0.458
5,000	EDA	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	ECZ	2	<0.388	0.341	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	EDA	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	ECZ	1	<0.388	0.342	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDA	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDA	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191

(Sheet 5 of 6)

C6

Table C1 (Concluded)

Carbon Type: Norit Hydrodarco 4000

Carbon Dosage mg/ℓ	Lot #	Rep	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
0	EDE	1	<0.388	<0.270	<0.767	<1.16	<1.11	1.680	<1.54	5.45	<0.191
0	EDE	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
0	EDF	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	EDC	1	<0.388	0.366	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	EDD	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	EDC	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	EDD	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
100	EDE	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	5.49	<0.191
100	EDE	3	<0.388	<0.270	<0.767	<1.16	<1.11	1.800	<1.54	<0.617	<0.191
500	EDF	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDC	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
500	EDC	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDF	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDC	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
1,000	EDE	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	EDE	1	<0.388	<0.270	<0.767	<1.16	<1.11	1.670	<1.54	5.32	<0.191
5,000	EDF	2	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
5,000	EDF	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDC	1	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDH	2	1.14	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
20,000	EDD	3	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191

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Table C2
Carbon Isotherm Study Quality Control Data - Blanks

Lot #	Date	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
ECY	3/27/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
ECZ	3/27/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EDA	3/27/91	0.851	0.95	1.59	1.66	1.61	1.52	3.73	1.92	0.595
EDB	3/27/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EDC	3/27/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EDD	3/27/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EDE	3/27/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EDF	3/27/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EDG	3/27/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EDH	3/27/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191

Table C3
Carbon Isotherm Study Quality Control Data Spike Results - Amount

Lot #	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
ECY	High	18.600	20.900	39.600	41.000	43.200	40.200	86.200	44.600	14.600
ECY	High	18.600	20.900	39.600	41.000	43.200	40.200	86.200	44.600	14.600
ECY	Low	0.855	0.524	1.470	2.320	2.290	2.330	3.250	1.310	0.352
ECZ	High	18.700	20.900	40.100	41.700	43.300	40.500	87.800	45.100	14.500
ECZ	High	18.700	20.900	40.100	41.700	43.300	40.500	87.800	45.100	14.500
ECZ	Low	0.762	0.481	1.380	2.180	2.130	1.980	3.040	1.180	0.349
EDA	High	18.300	20.600	39.300	40.600	42.600	39.300	85.900	44.000	13.800
EDA	High	18.300	20.600	39.300	40.600	42.600	39.300	85.900	44.000	13.800
EDA	Low	0.798	0.509	1.420	2.260	2.190	2.170	3.200	1.250	0.316
EDB	High	18.300	20.600	38.700	40.500	42.400	39.200	85.200	43.700	14.400
EDB	High	18.300	20.600	38.700	40.500	42.400	39.200	85.200	43.700	14.400
EDB	Low	0.831	0.525	1.450	2.310	2.260	2.130	3.250	1.320	0.341
EDC	High	18.900	21.200	40.300	41.600	43.800	40.700	87.400	45.300	14.300
EDC	High	18.900	21.200	40.300	41.600	43.800	40.700	87.400	45.300	14.300
EDC	Low	0.831	0.511	1.450	2.280	2.230	2.210	3.200	1.290	0.309
EDD	High	18.000	20.200	38.500	39.600	41.700	38.800	83.000	43.100	13.400
EDD	High	18.000	20.200	38.500	39.600	41.700	38.800	83.000	43.100	13.400

(Continued)

Table C3 (Concluded)

Lot #	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
EDD	Low	0.849	0.528	1.470	2.330	2.270	2.210	3.270	1.290	0.332
EDE	High	18.000	20.200	38.400	39.800	41.900	38.900	82.400	43.300	13.500
EDE	High	18.000	20.200	38.400	39.800	41.900	38.900	82.400	43.300	13.500
EDE	Low	0.839	0.515	1.450	2.310	2.250	2.100	3.190	1.260	0.332
EDF	High	18.800	21.000	40.100	41.600	43.600	40.500	87.000	45.000	14.100
EDF	High	18.800	21.000	40.100	41.600	43.600	40.500	87.000	45.000	14.100
EDF	Low	0.816	0.513	1.440	2.250	2.200	20.070	3.200	1.230	0.323
EDG	High	20.200	20.100	38.000	41.500	41.700	40.600	86.800	43.800	16.000
EDG	High	20.200	20.100	38.000	41.500	41.700	40.600	86.800	43.800	16.000
EDG	Low	0.877	0.559	1.510	2.360	2.310	2.170	3.420	1.330	0.338
EDH	High	19.900	19.900	37.600	41.600	41.300	40.100	86.600	43.200	15.400
EDH	High	19.900	19.900	37.600	41.600	41.300	40.100	86.600	43.200	15.400
EDH	Low	0.830	0.514	1.490	2.370	2.270	2.140	3.290	1.290	0.353

Table C4
Carbon Isotherm Study Quality Control Data Spike Results - Amount Recovered

Lot #	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
ECY	High	17.900	20.100	37.000	37.400	39.300	32.300	79.700	42.900	11.600
ECY	High	11.100	12.400	22.500	22.100	23.500	20.400	49.000	26.700	7.100
ECY	Low	0.935	0.529	1.400	2.230	2.010	2.060	3.230	1.230	0.265
ECZ	High	17.500	19.700	36.500	36.800	38.700	28.800	81.600	41.700	11.500
ECZ	High	17.600	20.100	37.400	38.300	39.800	28.200	83.300	41.100	11.400
ECZ	Low	0.848	0.520	1.400	2.230	2.070	1.870	3.040	1.290	0.200
EDA	High	15.600	17.200	31.900	30.800	32.500	25.700	71.000	38.400	11.500
EDA	High	17.000	18.800	34.700	33.500	35.500	26.300	78.100	40.800	12.000
EDA	Low	0.789	0.489	1.140	1.940	1.740	1.830	2.860	1.030	0.007
EDB	High	17.000	19.300	35.500	35.300	37.400	26.400	79.300	40.700	13.400
EDB	High	17.700	20.300	37.300	38.000	39.800	26.800	83.100	42.600	14.000
EDB	Low	0.767	0.481	1.230	1.870	1.820	1.570	2.860	1.150	0.289
EDC	High	17.300	19.700	36.400	36.600	38.600	28.800	80.400	42.100	13.600
EDC	High	17.800	20.300	37.500	37.700	39.800	29.200	82.800	42.500	13.800
EDC	Low	0.800	0.544	1.400	2.410	2.220	2.380	3.170	1.250	0.318
EDD	High	17.200	19.400	36.600	36.100	38.200	24.400	79.300	39.600	12.800
EDD	High	17.500	19.800	37.400	36.800	39.100	28.800	81.400	42.000	13.100

(Continued)

Table C4 (Concluded)

Lot #	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
EDD	Low	0.756	0.490	1.310	2.150	2.010	2.120	2.940	1.180	0.288
EDE	High	17.200	19.300	35.500	35.300	37.400	29.700	78.100	41.300	13.200
EDE	High	17.000	19.200	35.500	35.600	37.600	28.900	77.400	41.000	13.200
EDE	Low	0.783	0.470	1.260	2.010	1.940	1.710	2.780	1.100	0.327
EDF	High	17.100	19.200	35.900	35.700	37.700	28.300	78.900	41.300	13.000
EDF	High	17.400	19.600	35.700	35.000	36.900	18.300	80.600	39.400	12.900
EDF	Low	0.777	0.477	1.280	2.170	1.950	2.100	2.850	1.200	0.298
EDG	High	17.700	18.100	31.800	33.700	33.900	28.200	78.300	38.400	13.900
EDG	High	17.500	18.100	32.300	34.500	34.600	27.400	78.400	38.100	14.000
EDG	Low	0.712	0.468	1.180	1.970	1.820	1.910	2.810	1.110	0.265
EDH	High	18.700	19.000	34.600	36.800	36.900	27.500	82.300	40.700	14.700
EDH	High	18.200	18.500	33.900	36.900	36.500	12.200	80.700	33.000	14.200
EDH	Low	0.790	0.502	1.290	2.240	2.000	1.820	2.970	1.210	0.288

Appendix C   Analytical and Quality Control Results

Table C5
Carbon Isotherm Study Quality Control Data Spike Results - Percent Recovered

Lot #	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
ECY	High	96.237	96.172	93.434	91.220	90.972	80.348	92.459	96.188	79.452
ECY	High	59.677	59.330	56.818	53.902	54.398	50.746	56.845	59.865	48.630
ECY	Low	109.357	100.954	95.238	96.121	87.773	88.412	99.385	93.893	75.284
ECZ	High	93.583	94.258	91.022	88.249	89.376	71.111	92.938	92.461	79.310
ECZ	High	94.118	96.172	93.267	91.847	91.917	69.630	94.875	91.131	78.621
ECZ	Low	111.286	108.108	101.449	102.294	97.183	94.444	100.000	109.322	57.307
EDA	High	85.246	83.495	81.170	75.862	76.291	65.394	82.654	87.273	83.333
EDA	High	92.896	91.262	88.295	82.512	83.333	66.921	90.920	92.727	86.957
EDA	Low	98.872	96.071	80.282	85.841	79.452	84.332	89.375	82.400	2.082
EDB	High	92.896	93.689	91.731	87.160	88.208	67.347	93.075	93.135	93.056
EDB	High	96.721	98.544	96.382	93.827	93.868	68.367	97.535	97.483	97.222
EDB	Low	92.298	91.619	84.828	80.952	80.531	73.709	88.000	87.121	84.751
EDC	High	91.534	92.925	90.323	87.981	88.128	70.762	91.991	92.936	95.105
EDC	High	94.180	95.755	93.052	90.625	90.868	71.744	94.737	93.819	96.503
EDC	Low	96.270	106.458	96.552	105.702	99.552	107.692	99.063	96.899	102.913
EDD	High	95.556	96.040	95.065	91.162	91.607	62.887	95.542	91.879	95.522
EDD	High	97.222	98.020	97.143	92.929	93.765	74.227	98.072	97.448	97.761

(Continued)

Table C5 (Concluded)

Lot #	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
EDD	Low	89.046	92.803	89.116	92.275	88.546	95.928	89.908	91.473	86.747
EDE	High	95.556	95.545	92.448	88.693	89.260	76.350	94.782	95.381	97.778
EDE	High	94.444	95.050	92.448	89.447	89.737	74.293	93.932	94.688	97.778
EDE	Low	93.325	91.262	86.897	87.013	86.222	81.429	87.147	87.302	98.494
EDF	High	90.957	91.429	89.526	85.817	86.468	69.877	90.690	91.778	92.199
EDF	High	92.553	93.333	89.027	84.135	84.633	45.185	92.644	87.556	91.489
EDF	Low	95.221	92.982	88.889	96.444	88.636	101.449	89.063	97.561	92.260
EDG	High	87.624	90.050	83.684	81.205	81.295	69.458	90.207	87.671	86.875
EDG	High	86.634	90.050	85.000	83.133	82.974	67.488	90.323	86.986	87.500
EDG	Low	81.186	83.721	78.146	83.475	78.788	88.018	82.164	83.459	78.402
EDH	High	93.970	95.477	92.021	88.462	89.346	68.579	95.035	94.213	95.455
EDH	High	91.457	92.965	90.160	88.702	88.378	30.424	93.187	76.389	92.208
EDH	Low	95.181	97.665	86.577	94.515	88.106	85.047	90.274	93.798	81.586

Appendix D
Analytical and Quality Control Results for Pilot Column Tests

Table D1
Carbon Chemical Study Raw Chemical Analysis

Column ID	Lot No.	Date	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
4	EET	10/02/91	<0.543	<0.378	<1.07	<1.62	<1.55	<1.22	<2.16	<0.864	<0.267
12	EET	10/02/91	<0.582	<0.405	<1.15	<1.74	<1.66	<1.30	<2.31	<0.926	<0.286
12	EET	9/13/91	<0.621	<0.432	<1.23	<1.86	<1.78	<1.39	<2.46	<0.987	<0.306
4	EET	9/13/91	<0.582	<0.405	<1.15	<1.74	<1.66	<1.30	<2.31	<0.926	<0.286
1	EEP	9/12/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
2	EEP	9/12/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
9	EEP	9/12/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
10	EEP	9/12/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
INF	EEP	9/12/91	<0.388	<0.270	<0.767	<1.16	<1.11	1.26	<1.54	5.21	<0.191
12	EEU	10/14/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12	EEU	10/15/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
4	EEU	10/14/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
4	EEU	10/15/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
INF	EEU	10/02/91	<0.388	<0.270	<0.767	<1.16	<1.11	1.23	<1.54	5.25	<0.191
3	EEW	10/31/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191

(Sheet 1 of 5)

Note: INF = Influent; INC4 = Influent column 4; 4-INF = Column 4 influent; 4-6 = Column 4 at 6 in.; 4-12 = Column 4 at 12 in.; 4-18 = Column 4 at 18 in.; 4-30 = Column 4 at 30 in.; 4-36 = Column 4 at 36 in.; 4-EFF = Column 4 effluent; 11-INF = Column 11 influent; 11-6 = Column 11 at 6 in.; 11-12 = Column 11 at 12 in.; 11-24 = Column 11 at 24 in.; 11-30 = Column 11 at 30 in.; 11-EFF = Column 11 effluent; 12-INF = Column 12 influent; 12-6 = Column 12 at 6 in.; 12-12 = Column 12 at 12 in.; 12-24 = Column 12 at 24 in.; 12-30 = Column 12 at 30 in.; 12-EFF = Column 12 effluent.

Table D1 (Continued)

Column ID	Lot No.	Date	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
4	EEW	10/31/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
11	EEW	10/31/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12	EEW	10/31/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
INF	EEW	8/29/91	<0.388	<0.270	<0.767	<1.16	<1.11	1.40	<1.54	5.44	<0.191
INF	EEW	11/01/91	<0.388	<0.270	<0.767	<1.16	<1.11	1.26	<1.54	5.01	<0.191
12	EFC	12/05/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
4	EFC	12/05/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
INF	EFC	12/05/91	<0.388	<0.270	<0.767	<1.16	<1.11	1.21	<1.54	4.44	<0.191
12	EFC	12/04/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
4	EFC	12/04/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
4	EFI	12/18/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12	EFI	12/18/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
INF	EFI	12/19/91	<0.388	<0.270	<0.767	<1.16	<1.11	1.20	<1.54	4.59	<0.191
4	EFI	12/19/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12	EFI	12/19/91	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
4	EFJ	1/01/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12	EFJ	1/01/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
INF	EFJ	1/02/92	<0.388	<0.0270	<0.767	<1.16	<1.11	1.11	<1.54	3.91	<0.191
4	EFJ	1/02/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12	EFJ	1/02/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191

(Sheet 2 of 5)

Appendix D   Analytical and Quality Control Results

Table D1 (Continued)

Column ID	Lot No.	Date	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
4	EFL	1/15/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
4	EFL	1/16/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12	EFL	1/15/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12	EFL	1/16/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12	EFR	1/30/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
INF	EFR	1/30/92	<0.388	<0.270	<0.767	<1.16	<1.11	1.23	<1.54	4.38	<0.191
INF	EFR	2/19/92	<0.388	<0.270	<0.767	<1.16	<1.11	1.14	<1.54	3.95	<0.191
4-INF	EFR	2/19/92	<0.388	<0.270	<0.767	<1.16	<1.11	1.15	<1.54	4.03	<0.191
4	EFR	1/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
4	EFR	1/30/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12	EFR	1/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
INF	EFS	3/05/92	<0.388	<0.270	<0.767	<1.16	<1.11	1.05	<1.54	4.06	<0.191
4-6	EFS	3/05/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.855	<1.54	3.25	<0.191
4-12	EFS	3/05/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.552	<1.54	2.33	<0.191
4-18	EFS	3/05/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.434	<1.54	1.39	<0.191
4-24	EFS	3/05/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.434	<1.54	0.777	<0.191
4-30	EFS	3/05/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.434	<1.54	0.471	<0.191
4-36	EFS	3/05/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.434	<1.54	<0.309	<0.191
4-INF	EFV	4/17/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.838	<1.54	3.69	<0.191
4-6	EFV	4/17/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.675	<1.54	3.18	<0.191

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Appendix D   Analytical and Quality Control Results

Table D1 (Continued)

Column ID	Lot No.	Date	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
4-12	EFV	4/17/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.541	<1.54	2.70	<0.191
4-18	EFV	4/17/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.468	<1.54	2.20	<0.191
4-30	EFV	4/17/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.434	<1.54	1.05	<0.191
4-36	EFV	4/17/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.434	<1.54	0.587	<0.191
4-INF	EGD	5/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
4-6	EGD	5/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.803	<1.54	3.43	<0.191
4-12	EGD	5/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.570	<1.54	2.47	<0.191
4-18	EGD	5/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	1.93	<0.191
4-30	EGD	5/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	1.02	<0.191
4-36	EGD	5/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	0.618	<0.191
4-EFF	EGD	5/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.955	<1.54	4.30	<0.191
INF	EGN	6/23/92	<0.388	<0.270	<0.767	<1.16	<1.11	1.08	<1.54	4.06	<0.191
6	EGN	6/23/92	<0.388	<0.270	<0.767	<1.16	<1.11	1.02	<1.54	3.67	<0.191
12	EGN	6/23/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.807	<1.54	2.98	<0.191
18	EGN	6/23/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.601	<1.54	2.19	<0.191
30	EGN	6/23/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	1.32	<0.191
36	EGN	6/23/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	0.80	<0.191
EFF	EGN	6/23/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
11-INF	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	1.22	<1.54	4.25	<0.191
11-6	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.860	<1.54	2.99	<0.191

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Table D1 (Concluded)

Column ID	Lot No.	Date	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
11-12	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.517	<1.54	1.84	<0.191
11-24	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	0.395	<0.191
11-30	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12-INF	EGO	6/26/92	<0.388	<0.270	<0.767	<1.16	<1.11	1.31	<1.54	4.24	<0.191
12-6	EGO	6/26/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.589	<1.54	1.89	<0.191
12-12	EGO	6/26/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	0.762	<0.191
12-24	EGO	6/26/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12-30	EGO	6/26/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
12-EFF	EGO	6/26/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
11-EFF	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
4-INF	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	1.13	<1.54	4.24	<0.191
4-6	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.998	<1.54	3.83	<0.191
4-12	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.796	<1.54	3.22	<0.191
4-18	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	0.609	<1.54	2.76	<0.191
4-30	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	1.66	<0.191
4-36	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	1.08	<0.191
4-EFF	EGO	6/29/92	<0.388	<0.270	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191

(Sheet 5 of 5)

Table D2
Carbon Chemical Study Quality Control Data - Blanks

Lot No.	Date	135 TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
EET	9/13/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EEP	9/12/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EEU	10/31/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EEW	10/31/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EFC	12/11/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EFI	12/19/91	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EFJ	1/02/92	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EFL	1/16/92	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EFR	1/30/92	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EFS	3/05/92	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EFV	4/27/92	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EGD	5/29/92	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191
EGO	6/29/92	<0.388	<0.27	<0.767	<1.16	<1.11	<0.869	<1.54	<0.617	<0.191

Table D3
Carbon Chemical Study Quality Control Data Spike Results - Amount

Lot No.	Date	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
EET	9/13/91	High	17.800	19.200	36.700	39.900	40.300	38.800	102.000	39.600	15.500
EET	9/13/91	High	17.800	19.200	36.700	39.900	40.300	38.800	102.000	39.600	15.500
EET	9/13/91	Low	0.801	0.556	1.450	2.330	2.300	2.260	3.590	1.240	0.375
EEP	9/12/91	High	18.200	18.800	38.100	41.300	41.700	40.200	101.000	41.300	12.500
EEP	9/12/91	High	18.200	18.800	38.100	41.300	41.700	40.200	101.000	41.300	12.500
EEP	9/12/91	Low	0.821	0.573	1.520	2.330	2.340	2.310	3.730	1.260	0.239
EEU	10/31/91	High	17.700	19.100	36.900	40.600	39.800	38.900	102.000	39.600	15.300
EEU	10/31/91	High	17.700	19.100	36.900	40.600	39.800	38.900	102.000	39.600	15.300
EEU	10/31/91	Low	0.828	0.554	1.450	2.380	2.260	2.300	3.620	1.270	0.427
EEW	11/08/91	High	18.500	19.400	36.200	37.200	38.300	39.200	86.800	39.000	13.200
EEW	11/08/91	High	18.500	19.400	36.200	37.200	38.300	39.200	86.800	39.000	13.200
EEW	11/08/91	Low	0.855	0.549	1.530	2.260	2.290	2.270	3.080	1.200	0.323
EFC	12/11/91	High	19.300	20.000	38.000	39.000	39.200	40.600	91.000	40.300	12.500
EFC	12/11/91	High	19.300	20.000	38.000	39.000	39.200	40.600	91.000	40.300	12.500
EFC	12/11/91	Low	0.897	0.551	1.620	2.430	2.380	2.420	3.120	1.270	0.364
EFI	12/19/91	High	20.100	21.100	39.900	39.400	42.500	42.700	93.800	42.400	13.400
EFI	12/19/91	High	20.100	21.100	39.900	39.400	42.500	42.700	93.800	42.400	13.400
EFI	12/19/91	Low	0.905	0.589	1.750	2.370	2.470	2.520	3.350	1.290	0.412

(Continued)

Table D3 (Concluded)

Lot No.	Date	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
EFJ	1/02/92	High	18.900	19.500	37.900	42.000	41.200	41.600	86.700	40.000	14.100
EFJ	1/02/92	High	18.900	19.500	37.900	42.000	41.200	41.600	86.700	40.000	14.100
EFJ	1/02/92	Low	0.843	0.571	1.550	2.260	2.460	2.310	2.980	1.260	0.301
EFL	1/16/92	High	19.500	19.900	39.300	43.700	41.900	42.800	91.900	41.100	14.300
EFL	1/16/92	High	19.500	19.900	39.300	43.700	41.900	42.800	91.900	41.100	14.300
EFL	1/16/92	Low	0.849	0.560	1.450	2.160	2.200	2.380	3.040	1.280	0.261
EFR	1/29/92	High	20.600	21.200	41.900	46.900	44.700	45.100	93.600	43.500	14.500
EFR	1/29/92	High	20.600	21.200	41.900	46.900	44.700	45.100	93.600	43.500	14.500
EFR	1/29/92	Low	0.880	0.595	1.590	2.440	2.490	2.500	3.160	1.360	0.343
EFS	3/05/92	High	19.300	19.500	39.000	42.700	42.100	42.500	93.800	40.600	14.000
EFS	3/05/92	High	19.300	19.500	39.000	42.700	42.100	42.500	93.800	40.600	14.000
EFS	3/05/92	Low	0.852	0.533	1.460	2.270	2.340	2.310	3.170	1.280	0.383
EFV	4/27/92	High	18.800	19.300	42.800	44.600	40.900	37.700	104.000	45.000	15.100
EFV	4/27/92	High	18.800	19.300	42.800	44.600	40.900	37.700	104.000	45.000	15.100
EFV	4/27/92	Low	0.912	0.541	1.500	2.380	2.300	2.290	3.210	1.330	0.351
EGD	5/29/92	High	17.900	20.500	40.500	40.800	33.200	43.100	87.600	41.600	15.700
EGD	5/29/92	High	17.900	20.500	40.500	40.800	33.200	43.100	87.600	41.600	15.700
EGD	5/29/92	Low	0.792	0.599	1.590	1.670	1.980	1.860	2.820	1.150	0.307
EGO	6/29/92	High	18.500	20.500	43.200	40.700	41.200	43.500	89.700	43.100	13.400
EGO	6/29/92	High	18.500	20.500	43.200	40.700	41.200	43.500	89.700	43.100	13.400
EGO	6/29/92	Low	0.774	0.598	1.530	1.500	2.260	2.130	3.090	1.150	0.244

Appendix D   Analytical and Quality Control Results

Table D4
Carbon Chemical Study Quality Control Data Spike Results - Amount Recovered

Lot No.	Date	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
EET	9/13/91	High	16.700	18.000	33.700	35.700	36.500	28.000	92.700	37.300	14.200
EET	9/13/91	High	17.100	18.100	34.000	35.400	36.500	22.100	93.600	28.600	14.300
EET	9/13/91	Low	0.760	0.513	1.270	1.960	1.960	1.940	3.250	1.210	0.352
EEP	9/12/91	High	17.200	17.700	35.100	36.800	37.400	33.000	93.000	39.800	11.500
EEP	9/12/91	High	17.200	17.500	35.000	36.200	36.700	33.800	91.600	39.900	11.400
EEP	9/12/91	Low	0.788	0.517	1.280	1.870	1.920	2.000	3.210	1.190	0.204
EEU	10/31/91	High	16.800	18.100	33.500	35.500	35.3	31.9	91.7	38.6	14
EEU	10/31/91	High	16.600	17.900	33.300	34.700	34.900	32.800	92.700	38.400	13.900
EEU	10/31/91	Low	0.752	0.493	1.220	1.880	1.820	2.080	3.110	1.210	0.403
EEW	11/08/91	High	17.400	17.800	32.200	30.400	32.400	32.600	76.800	38.100	11.900
EEW	11/08/91	High	18.000	18.500	33.800	33.300	34.700	32.400	80.100	38.600	12.200
EEW	11/08/91	Low	0.825	0.509	1.330	1.840	1.950	2.140	2.750	1.250	0.300
EFC	12/11/91	High	17.300	18.200	33.500	34.000	34.300	25.600	78.500	28.800	11.200
EFC	12/11/91	High	18.000	19.000	34.800	35.200	35.900	29.400	85.200	32.200	11.600
EFC	12/11/91	Low	0.817	0.489	1.300	1.870	1.880	2.390	2.700	1.220	0.274
EFI	12/19/91	High	18.300	18.800	34.800	34.100	36.200	38.200	82.200	39.400	11.700
EFI	12/19/91	High	18.300	18.900	35.100	34.300	36.600	38.100	81.600	39.600	11.700
EFI	12/19/91	Low	0.882	0.526	1.460	2.050	2.180	2.270	2.820	1.380	0.304

(Continued)

Table D4 (Concluded)

Lot No.	Date	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
EFJ	1/02/92	High	18.200	18.500	35.600	38.500	38.200	32.700	76.100	38.800	12.900
EFJ	1/02/92	High	18.200	18.600	35.500	38.300	37.800	32.600	75.000	38.800	12.800
EFJ	1/02/92	Low	0.870	0.513	1.380	1.980	2.110	2.120	2.600	1.300	0.259
EFL	1/16/92	High	17.900	18.400	35.100	37.800	36.500	39.700	84.000	38.900	12.400
EFL	1/16/92	High	18.000	17.700	34.500	35.900	35.100	40.500	80.600	39.400	12.500
EFL	1/16/92	Low	0.814	0.521	1.320	1.960	1.980	2.320	1.860	1.280	0.243
EFR	1/29/92	High	18.300	16.900	34.600	30.200	30.900	42.000	70.500	40.400	12.600
EFR	1/29/92	High	18.600	18.300	36.100	37.500	36.600	41.700	77.000	40.400	12.800
EFR	1/29/92	Low	0.802	0.517	1.360	1.800	1.950	2.420	2.670	1.280	0.318
EFS	3/05/92	High	18.100	18.100	35.500	37.700	37.600	40.200	84.100	38.800	12.600
EFS	3/05/92	High	18.200	18.200	35.900	38.000	38.000	40.700	85.500	39.100	12.700
EFS	3/05/92	Low	0.0857	0.517	1.380	2.100	2.160	2.250	2.940	1.450	0.372
EFV	4/27/92	High	17.400	17.900	38.100	38.700	35.000	32.200	93.400	41.300	13.500
EFV	4/27/92	High	18.100	18.800	40.700	41.800	38.200	35.700	98.900	44.300	14.200
EFV	4/27/92	Low	0.897	0.509	1.390	2.040	2.070	2.370	2.990	1.270	0.336
EGD	5/29/92	High	17.000	19.300	37.600	37.000	30.300	28.000	78.400	39.200	14.600
EGD	5/29/92	High	16.900	19.100	37.200	36.300	30.100	28.100	77.700	39.300	14.500
EGD	5/29/92	Low	0.794	0.582	1.410	1.350	1.710	1.610	2.580	1.230	0.284
EGO	6/29/92	High	17.800	19.800	40.900	38.300	38.600	39.900	85.100	42.000	12.800
EGO	6/29/92	High	17.800	19.800	40.800	38.300	38.700	39.100	83.100	41.800	12.500
EGO	6/29/92	Low	0.724	0.571	1.400	1.370	2.070	2.070	2.900	1.170	0.209

Table D5
Carbon Chemical Study Quality Control Data Spike Results - Percent Recovered

Lot No.	Date	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
EET	9/13/91	High	93.820	93.750	91.826	89.474	90.571	72.165	90.882	94.192	91.613
EET	9/13/91	High	96.067	94.271	92.643	88.722	90.571	56.959	91.765	72.222	92.258
EET	9/13/91	Low	94.881	92.266	87.586	84.120	85.217	85.841	90.529	97.581	93.867
EEP	9/12/91	High	94.505	94.149	92.126	89.104	89.688	82.090	92.079	96.368	92.000
EEP	9/12/91	High	94.505	93.085	91.864	87.651	88.010	84.080	90.693	96.610	91.200
EEP	9/12/91	Low	95.981	90.227	84.211	80.258	82.051	86.580	86.059	94.444	85.356
EEU	10/31/91	High	94.915	94.764	90.786	87.438	88.693	82.005	89.902	97.475	91.503
EEU	10/31/91	High	93.785	93.717	90.244	85.468	87.688	84.319	90.882	96.970	90.850
EEU	10/31/91	Low	90.821	88.989	84.138	78.992	80.531	90.435	85.912	95.276	94.379
EEW	11/08/91	High	94.054	91.753	88.950	81.720	84.595	83.163	88.479	97.692	90.152
EEW	11/08/91	High	97.297	95.361	93.370	89.516	90.601	82.653	92.281	98.974	92.424
EEW	11/08/91	Low	96.491	92.714	86.928	81.416	85.153	94.273	89.286	104.167	92.879
EFC	12/11/91	High	89.637	91.000	88.158	87.179	87.500	63.054	86.264	71.464	89.600
EFC	12/11/91	High	93.264	95.000	91.579	90.256	91.582	72.414	93.626	79.901	92.800

(Continued)

Table D5 (Concluded)

Lot No.	Date	Type	135TNB	13DNB	246TNT	24DNT	26DNT	HMX	NB	RDX	TETRYL
EFI	12/19/91	High	91.045	89.573	87.970	87.056	86.118	89.227	86.994	93.396	87.313
EFI	12/19/91	Low	97.459	89.304	83.429	86.498	88.259	90.079	84.179	106.977	73.786
EFJ	1/02/92	High	96.296	94.872	93.931	91.667	92.718	78.606	87.774	97.000	91.489
EFJ	1/02/92	High	96.296	95.385	93.668	91.190	91.748	78.365	86.505	97.000	90.780
EFJ	1/02/92	Low	103.203	89.842	89.032	87.611	85.772	91.775	87.248	103.175	86.047
EFL	1/16/92	High	91.795	92.462	89.313	86.499	87.112	92.757	91.404	94.647	86.713
EFL	1/16/92	High	92.308	88.945	87.786	82.151	83.771	94.626	87.704	95.864	87.413
EFL	1/16/92	Low	95.878	93.036	91.034	90.741	90.000	97.479	61.184	100.000	93.103
EFR	1/29/92	High	88.835	79.717	82.578	64.392	69.128	93.126	75.321	92.874	86.897
EFR	1/29/92	High	90.291	86.321	86.158	79.957	81.879	92.461	82.265	92.874	88.276
EFR	1/29/92	Low	91.136	86.891	85.535	73.770	78.313	96.800	84.494	94.118	92.711
EFS	3/05/92	High	93.782	92.821	91.026	88.290	89.311	94.588	89.659	95.567	90.000
EFS	3/05/92	High	94.301	93.333	92.051	88.993	90.261	95.765	91.151	96.305	90.714
EFS	3/05/92	Low	100.587	86.998	94.521	92.511	92.308	97.403	92.744	113.281	97.128
EFV	4/27/92	High	92.553	92.746	89.019	86.771	85.575	85.411	89.808	91.778	89.404
EFV	4/27/92	High	96.277	97.409	95.093	93.722	93.399	94.695	95.096	98.444	94.040
EFV	4/27/92	Low	98.355	94.085	92.667	85.714	90.000	103.493	93.146	95.489	95.726

Appendix E
Empty-Bed Contact Time
(EBCT) Calculations for F-200
Carbon

Data for Exhaustion Curves and EBCT Calculations

Breakthrough first indicated:

Date	Height, in.	Gallons Processed	Carbon Bed Volume ft³	Approximate Time Operated days	Average Flow Rate
3/5/92	18	74,109	0.1309	180	0.286
4/17/92	30	93,643	0.2182	222	0.293
6/29/92	36	124,628	0.2618	289	0.299
				Average	0.293
Note: Given - F-200 carbon density 29 lb/ft³; full-scale plant flow = 1 MGD.					

Calculate EBCT

$$EBCT = \frac{carbon\ bed\ volume\ (ft^3) \times 7.48}{flow\ rate\ (gal/\text{min})}$$

Example using 3/5/92 data:

$$EBCT = \frac{(0.1309\ ft^3)(7.48)}{0.29\ gal/\text{min}} = \boxed{3.38}$$

Carbon usage calculations

$$\frac{lb\ carbon}{1{,}000\ gal\ of\ water\ treated} = \frac{(volume\ carbon\ ft^3)\left[density\ carbon\ \dfrac{lb}{ft^3}\right]}{volume\ of\ water\ treated\ at\ breakthrough\ (gal)} \times 1{,}000$$

Example using 3/5/92 data:

$$\frac{lb\ carbon}{1{,}000\ gal} = \frac{(0.1309\ ft^3)\left[29\ \dfrac{lb}{ft^3}\right]}{74{,}109\ gal} \times 1{,}000$$

$$\boxed{= 0.051\ \frac{lb\ carbon}{1{,}000\ gal}}$$

Carbon usage per day

$$\frac{lb\ carbon\ used}{day} = \left[\frac{lb\ carbon}{1{,}000\ gal}\right]\left[full\text{-}scale\ flow\ \frac{gal}{day}\right]$$

Example using 3/5/92 data:

$$\frac{lb\ carbon}{day} = \left[\frac{0.051\ lb}{1{,}000\ gal}\right]\left[\frac{1 \times 10^6\ gal}{day}\right] = \boxed{\frac{51\ lb}{day}}$$

Loading at breakthrough

$$\frac{lb\ RDX}{lb\ carbon} =$$

$$\frac{\left[\begin{array}{c}RDX\ come\ in\\ water,\ mg/\ell\end{array}\right]\left[\dfrac{1\ mg}{1{,}000\ \mu g}\right]\left[\dfrac{1\ g}{1{,}000\ mg}\right]\left[\dfrac{1\ \ell}{0.2642\ gal}\right]\left[\begin{array}{c}gal\ of\ water\\ processed\end{array}\right]\left[\dfrac{lb}{454\ g}\right]}{wt\ of\ carbon\ used}$$

Example using 3/5/92 data:

Average concentration of RDX in influent $= 4.5\ \dfrac{\mu g\ RDX}{\ell}$

But breakthrough $= \dfrac{1\ \mu g\ RDX}{\ell}$ so $\dfrac{4.5\ \mu g}{\ell} - \dfrac{1\ \mu g}{\ell} = \dfrac{3.5\ \mu g\ RDX}{\ell}$ on carbon

$$\dfrac{lb\ RDX}{lb\ carbon} =$$

$$\dfrac{\left[\dfrac{3.5\ \mu g\ RDX}{\ell}\right]\left[\dfrac{1\ mg}{1{,}000\ mg}\right]\left[\dfrac{1\ g}{1{,}000\ mg}\right]\left[\dfrac{1\ \ell}{0.2642\ gal}\right](74{,}109\ gal)\left[\dfrac{lb}{454\ g}\right]}{(0.1309\ ft^3\ carbon)\left[29\ \dfrac{lb}{ft^3}\right]}$$

$$= 5.69 \times 10^{-4}\ \dfrac{lb\ RDX}{lb\ carbon} = 0.057\%\ loading$$

Date	EBCT	lb Carbon Used	Gallons Processed at Breakthrough	Carbon lb/1,000 gal	Usage Per Day	Carbon Loading at Breakthrough (lb RDX/lb Carbon)	Percent Loading
3/15/92	3.38	3.4	74,109	0.051	51	5.69×10^{-4}	0.057
4/17/92	5.62	6.32	93,643	0.068	68	4.31×10^{-3}	0.043
6/29/92	6.72	7.59	124,628	0.061	61	4.78×10^{-4}	0.048

By plotting carbon usage/1,000 gal versus EBCT, a curve is generated. This curve (shown in Figure 28) shows that EBCT is increased carbon usage falls. For this data analysis, the curve is relatively constant, so a 3.38 EBCT is selected as optimal.

> *optimal EBCT for F-200 = 3.38 min*

Carbon volume calculations

Using an EBCT of 3.38 min

$$\text{volume of carbon } (ft^3) = EBCT \text{ (min)} \times \text{flow } \frac{ft^3}{\min} \text{ for the full-size plant}$$

$$\text{full-size plant flow rate } \frac{ft^3}{\min} = 1 \times 10^6 \frac{gal}{day}$$

or

$$\left[\frac{1 \times 10^6 \ gal}{day} \right] \left[\frac{1 \ day}{1{,}440 \ \min} \right] \left[\frac{1 \ ft^3}{7{,}148 \ gal} \right] = 92.84 \frac{ft^3}{\min} \ flow$$

$$\text{volume of carbon } ft^3 = (3.38 \text{ min}) \left[92.84 \ \frac{ft^3}{\min} \right]$$

$$\boxed{= 313 \ ft^3 \ of \ carbon}$$

Carbon adsorber dimensions calculations

Using the hydraulic loading used in the pilot high-flow system just prior to fluidization at 0.5 GPM or

$$\frac{0.5 \ gal/\min}{\substack{0.087 \ ft^2 \\ (area \ of \ column)}} = 5.74 \ gal/\min/ft^2$$

$$\begin{array}{c} \text{Area of adsorber} \\ (ft^2) \end{array} = \frac{\text{flow of full-scale plant } (gal/\min)}{\text{hydraulic loading used}}$$

$$= \frac{\left[1 \times 10^6 \ \frac{gal}{pay} \right] \left[\frac{1 \ day}{1{,}440 \ \min} \right]}{5.74}$$

Area of adsorber $= 120.9$ or $\boxed{121 \ ft^2}$

Using a circular adsorber

$$\text{Diameter of adsorber} = \sqrt{\frac{4 \times 121 \ ft}{\pi}}$$

$$\boxed{\text{Diameter of adsorber} = 12.4 \ ft}$$

Carbon bed depth =

$$= \frac{volume\ of\ carbon,\ ft^3}{area\ of\ adsorber,\ ft^2}$$

$$= \frac{313\ ft^3}{121\ ft^2} = \boxed{2.6\ ft}$$

While a 12-ft diam by 2.6-ft-high adsorber is optimal, this is a non-standard size. It was recommended by the design district (Omaha District, Mark Wichmah) to use a 20,000-lb carbon vessel that can be purchased in 10-ft diam size and is approximately 8 ft tall.

> *Two 10-ft diam by 8-ft-tall carbon vessels are recommended.*

Appendix F
RDX Breakthrough Calculations

Five sets of data were collected for the period of 05 March 1991 - 29 June 1992. The high-flow F-200 material (column set 1) data is shown below:

Sample Location	Date				
	3/5/92	4/17/92	5/29/92	6/23/92	6/29/92
	(RDX concentration in ppb)				
Influent	4.06	3.69	4.30	4.06	4.24
6 in.	3.25	3.18	3.43	3.67	3.83
12 in.	2.33	2.70	2.47	2.98	3.22
18 in.	1.39	2.20	1.93	2.19	2.76
30 in.	0.471	1.05	1.02	1.32	1.66
36 in.	<0.309	0.587	0.618	0.80	1.08
Effluent	<0.617	<0.617	<0.617	<0.617	<0.617

Each data set was regressed using Lotus-123's linear regression package as shown (using data set 05 March 1992 for example).

Regression of data set 05 March 1995.

By regressing the sample location height versus RDX concentration, the equation for the best fit line can be developed as shown below:

Regress
0		4.06
6		3.25
12	versus	2.33
18		1.37
30		0.47

The following regression output is obtained.

$$\text{Constant} = 3.915595$$
$$\text{Std Err of y Est} = 0.254872$$
$$\text{R Squared} = 0.97616$$
$$\text{No. - of Obers.} = 5$$
$$\text{Degrees of Freedom} = 3$$

$$\text{x coefficient(s)} = -0.12238$$
$$\text{std err of coef.} = 0.011042$$

- The most important values are the constant, x coefficient, and the R^2 value. Putting these into the equation of a straight line

$$y = mx + b$$

where

y = RDX concentration

m = slope

x = sample location height

b = y intercept

and from the Lotus printout values

b = constant and m = x coefficient

the equation of the line becomes

$$y = (-0.122)x + 3.915 \tag{F1}$$

with a R^2 value (goodness of fit) of 0.97616. This is a "good fit." Thus, a straight line estimates the actual data. By using this equation, the RDX concentration can be calculated as shown below:

Sample Location Height (x)	Actual RDX Concentration	Predicted RDX Concentration (y)
0	4.06	3.92
6	3.25	3.18
12	2.33	2.45
18	1.39	1.72
30	0.47	0.26

Plotting this data as shown in Figure F1 shows that this is a good approximation.

Now using Equation 1 and setting y to 1 (our breakthrough criteria of 1 ppb RDX) yields

$$1 = (-0.122)x + 3.915$$

Solving for x yields

$$1 - 3.915 = -0.122x$$

$$-2.915 = -0.122x$$

$$\frac{-2.915}{-0.122} = x$$

$$23.89 \ in. = x$$

$$\boxed{x = 23.89 \ in.}$$

This is the height at which a breakthrough of 1 ppb RDX will occur on 05 March 1992.

This procedure was repeated for all subsequent dates as shown:

17 April 1992.

$$y = (-0.08717)x + 3.7164 \qquad R^2 = 0.999015$$

@ y = 1 ppb RDX $\qquad \boxed{x = 31.16 \ in.}$

This regression data is shown in Figure F2.

29 May 1992

$$y = (-0.09964)x + 3.98847 \qquad R^2 = 0.967677$$

@ y = 1 ppb RDX $\qquad \boxed{x = 29.99 \ in.}$

This regression data is shown in Figure F3.

23 June 1992

$$y = (-0.0929)x + 4.0826 \qquad R^2 = 0.99112$$

@ y = 1 ppb RDX $\qquad \boxed{x = 37.32 \ in.}$

This regression data is shown in Figure F4.

29 June 1992

$$y = (-0.08846)x + 4.30211 \qquad R^2 = 0.99844$$

$$@ \; y = 1 \text{ ppb RDX} \qquad \boxed{x = 37.32 \text{ in.}}$$

This regression data is shown in Figure F5.
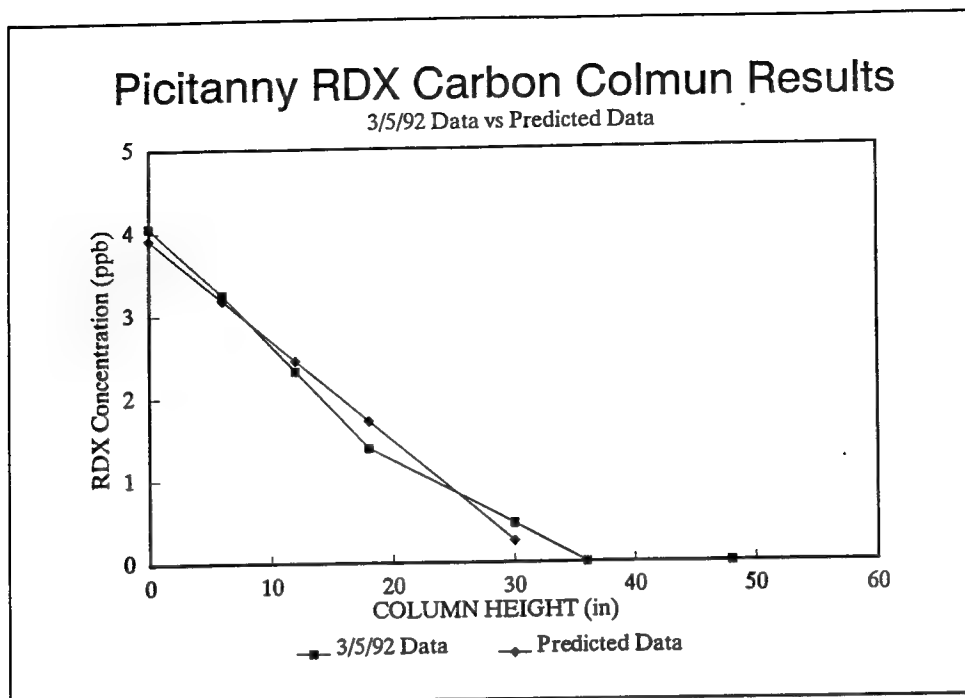
Figure F1. Carbon column height versus RDX concentration for sampling period of 05 March 1992. Actual as well as regression data is presented
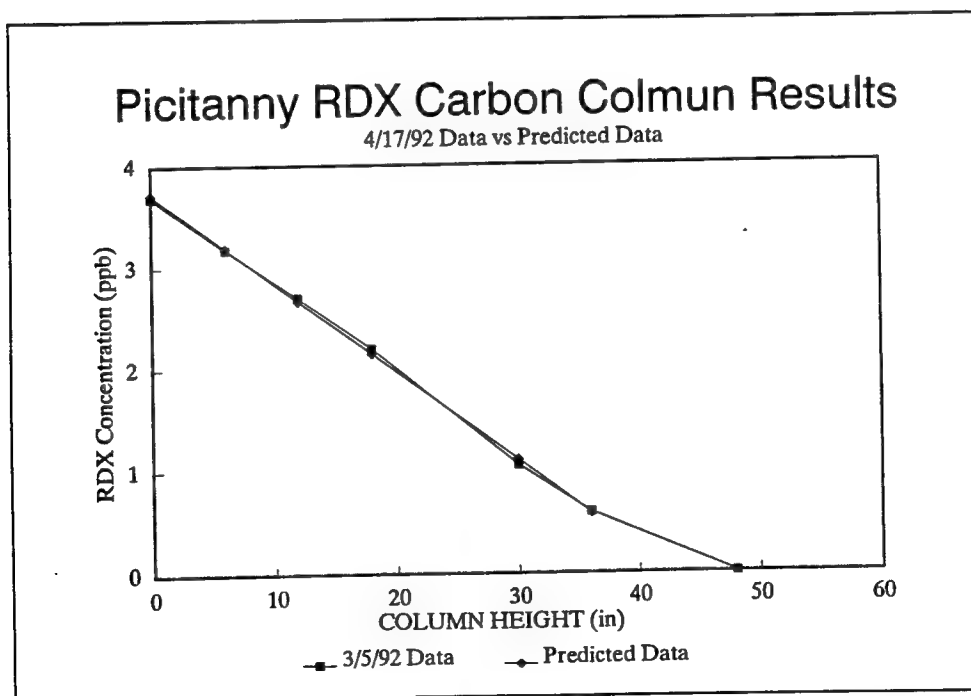
Figure F2. Carbon column height versus RDX concentration for sampling period of 17 April 1992. Actual as well as regression data is presented

Appendix F   RDX Breakthrough Calculations
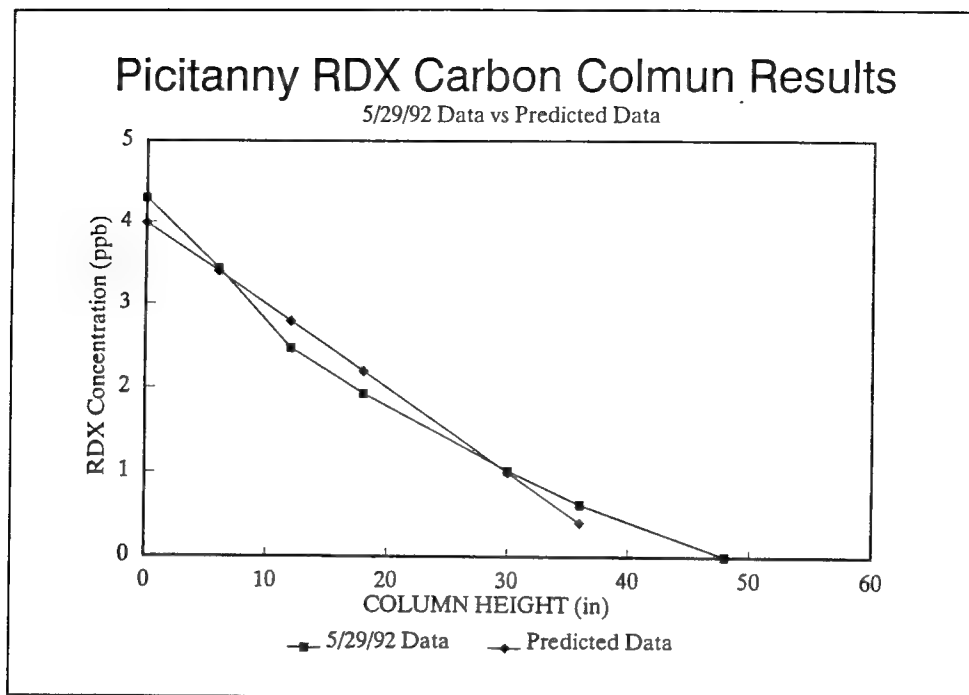
Figure F3. Carbon column height versus RDX concentration for sampling
period of 29 May 1992. Actual as well as regression data is
presented
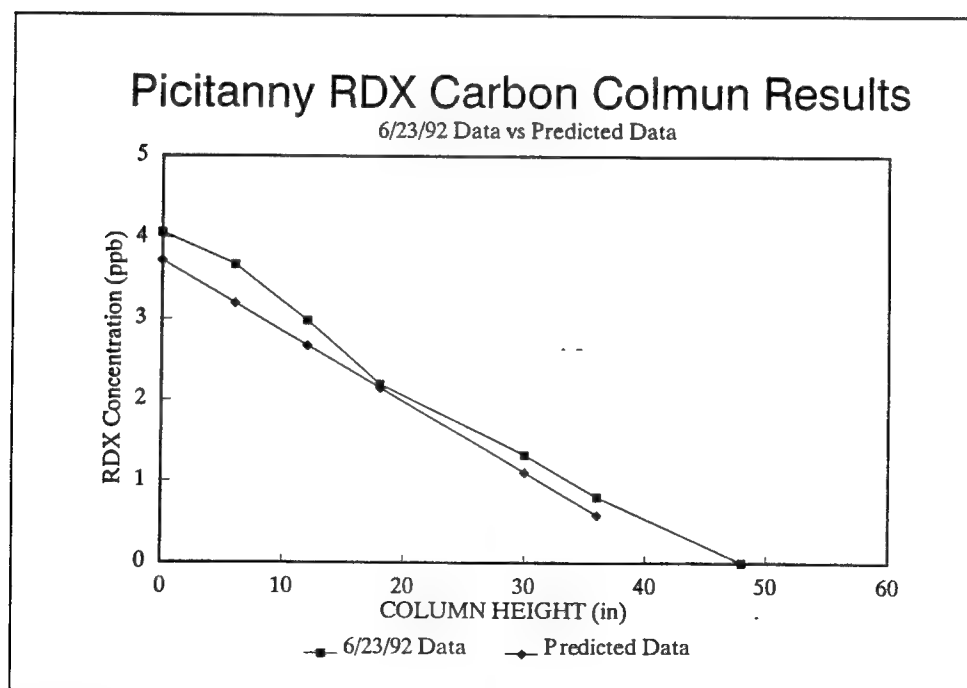
Figure F4. Carbon column height versus RDX concentration for sampling
period of 23 June 1992. Actual as well as regression data is
presented
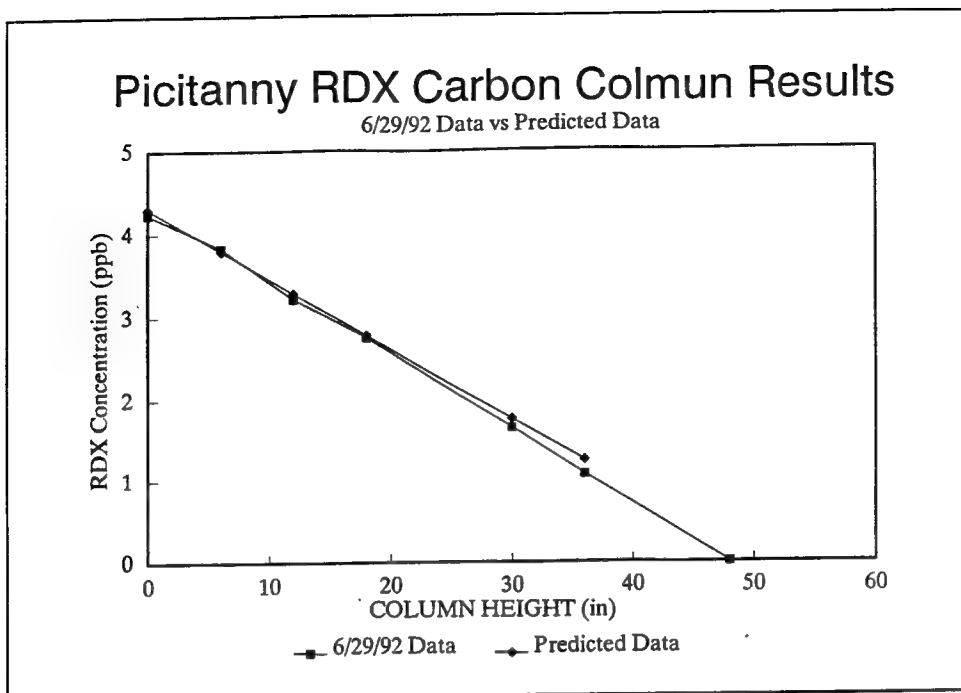
Figure F5. Carbon column height versus RDX concentration for sampling period of 29 June 1992. Actual as well as regression data is presented

Appendix G
Carbon Usage Calculations for F-200 Carbon

In the pilot study, 4-in. columns were used. Thus:

$$area = \pi(r)^2 = \pi\left(\frac{2}{12}\right)^2 = 0.08727 \; ft^2 = area \; of \; column$$

From the text, the following regression equation was used

$$y = (0.000209)x + 9.1909 \; at \; a \; flow \; of \; x = 124,628$$

From this equation, it is calculated that a carbon height of $\underline{y = 35.23 \; in.}$ will treat 124,628 gal of RDX-contaminated water.

The volume of carbon to treat 124,628 gal of RDX contaminated water is

$$(35.23 \; in.) \left[\frac{1 \, ft}{12 \, in.}\right] (0.08727 \; ft^2) = 0.256 \; ft^3 \; of \; carbon \; to \; treat \; 124,628 \; gal$$

The Calgon literature states that F-200 has a density of 29 lb/ft^3. The amount of carbon needed can be calculated as follows.

$$(0.256 \; ft^3)\left[\frac{29 \, lb}{ft^3}\right] = 7.43 \; lb \; of \; carbon \; per \; 124,628 \; gal$$

or

$$\frac{7.43 \; lb}{124,628 \; gal} = \frac{5.96174 \times 10^{-5} \; lb}{gal} = \boxed{\frac{59.6 \; lb \; of \; carbon}{million \; gal \; of \; water}}$$

This also equals

$$\frac{0.256 \; ft^3}{124,628 \; gal} = \boxed{\frac{2.05 \; ft^3 \; of \; carbon}{million \; gal \; of \; water}} = carbon \; F\text{-}200 \; usage$$

To calculate the change over period of a 20,000 lb vessel, use the following.

$$\frac{7.43 \; lb \; carbon}{124,628 \; gal \; of \; water} = \frac{20,000 \; lb \; carbon}{x \; gal \; of \; water}$$

$$(7.43)(x) = (124,628)(20,000)$$

$$7.43(x) = 2,492 \times 10^9$$

$$x = 3.35 \times 10^8 \; gal \; of \; water$$

3.35×10^8 gal of water can pass through one 20,000-lb carbon vessel prior a required change. Using the 1-MGD plant gives the following information.

$$(3.35 \times 10^8 \; gal) \left[\frac{1 \; day}{1 \times 10^6 \; gal} \right] \cong \boxed{\begin{array}{c} 335 \; days \; of \; operation \; prior \\ to \; a \; required \; change \end{array}}$$

and

$$\frac{20,000 \; lb \; of \; carbon}{335 \; days} = \frac{59.70 \; lb}{day} = \boxed{\frac{21,791 \; lb \; carbon}{year}}$$

Appendix H
Carbon Usage Calculations for
H-4000 Carbon

Regression of the H-4000 Data Set Using the Procedure Described in Appendix G

27 June 1992

$$y = mx + b$$

$$y = (-0.28983)x + 4.03633$$

$$R^2 = 0.9604$$

@ $y = 1$ ppb RDX

$$\boxed{x = 10.47 \text{ in.}}$$

A plot of this regression data is presented in Figure H1.

29 June 1992

$$y = (-0.15869)x + 4.035$$

$$R^2 = 0.97928$$

@ $y = 1$ ppb RDX

$$\boxed{x = 19.12 \text{ in.}}$$

A plot of this regression data is presented in Figure H2.

Using the 29 June 1992 data of 19.12 in. of carbon in a 4-in. diam column (or 0.08727 ft² = 4-in. area) yields

$$(19.12 \ in.) \left[\frac{1 \ ft}{12 \ in.} \right] (0.08727 \ ft^2) = 0.14487 \ ft^3 \ of \ carbon$$

@ 29 June 1992, 73,591 gal of water have passed through the column, so use a ratio to get full-scale usage

$$\frac{0.14487 \ ft^3 \ of \ carbon}{73,591 \ gal} = \frac{1.96 \times 10^{-6} \ ft^3 \ of \ carbon}{gal \ of \ water \ treated}$$

This is

$$\frac{1.968 \ ft^3 \ of \ carbon}{million \ gal} \ for \ H\text{--}4000$$

Summary

$$H\text{--}4000 \ carbon \ usage = \frac{1.96 \ ft^3}{million \ gal}$$

$$F\text{--}200 \ carbon \ usage = \frac{2.05 \ ft^3}{million \ gal}$$

These are very close; the conservative

$$\frac{2.05 \ ft^3}{million \ gal}$$

will be used in all future calculations.
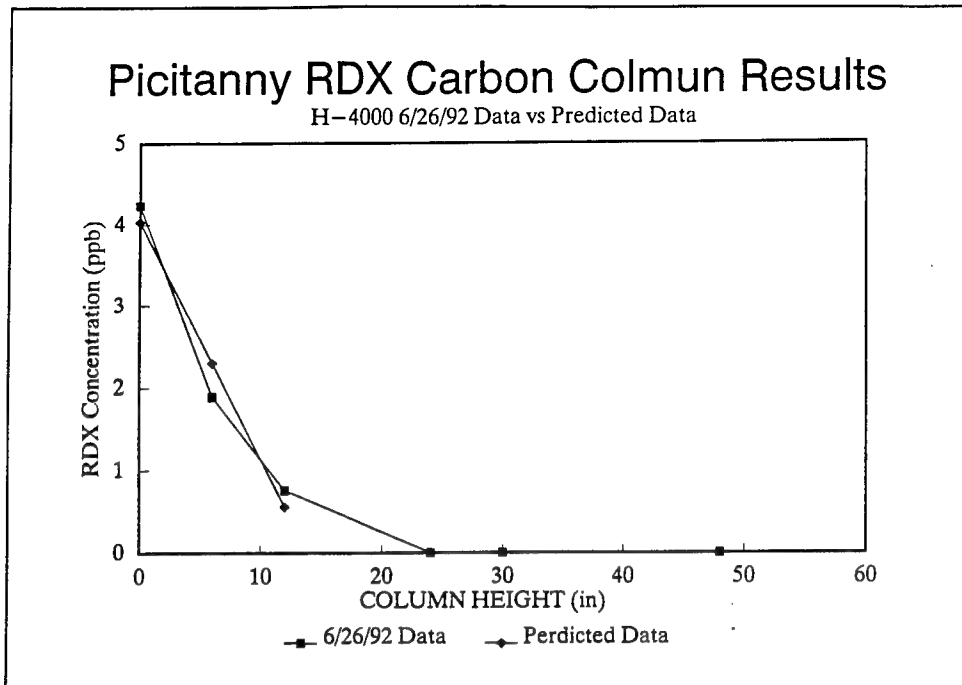
Figure H1. Picatinny RDX carbon column results for H-4000 data collected on 26 June 1992, regression and actual data
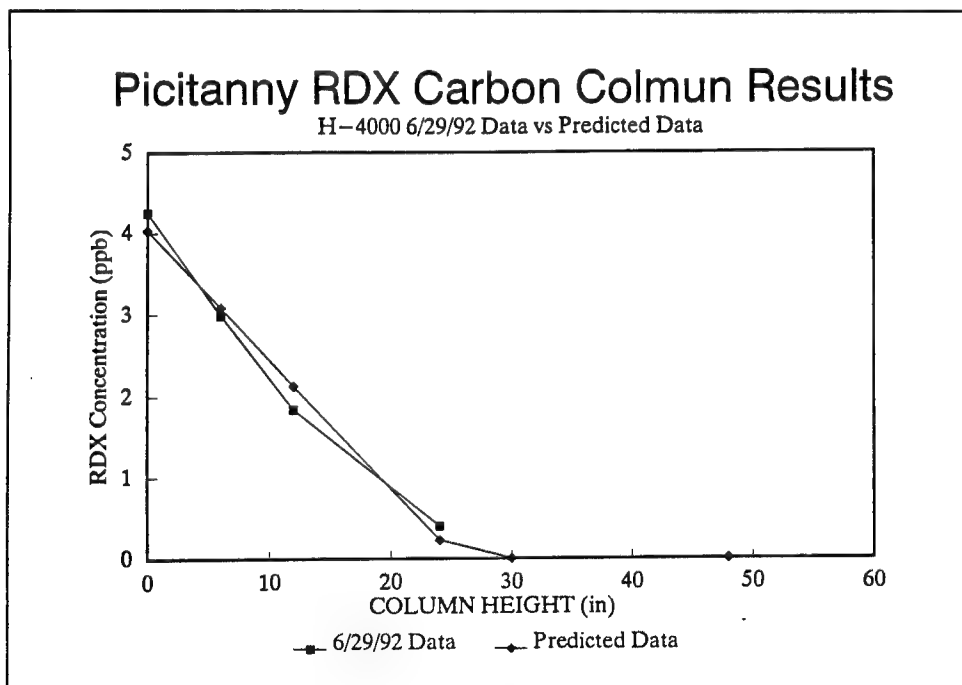
Figure H2. Picatinny RDX carbon column results for H-4000 data collected on 29 June 1992, regression and actual data

Appendix I
Request for Design Work

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
3909 HALLS FERRY ROAD
VICKSBURG, MISSISSIPPI 39180-6199

August 23, 1992

REPLY TO
ATTENTION OF

Environmental Laboratory

Jenelle Mabis
CEMRO-ED-DK
US Army Corps of Engineers
215 N 17 Street
Omaha, NE 68102-4978

Dear Ms. Mabis

As we discussed enclosed or attached is a copy of the
Picitanny Water Treatment Plant (Bld 1383) drawings. In addition
the following information is provided:

1. The Design flow rate of the Plant is 1MGD

2. Roy Oaks (the plant operator) said the sand filter operate at
a pressure of around 30 psi

3. Roy said that the treated water pumps operated at a pressure
of 130 psi

4. Roy said that the treated water was used for some fire
protection? I'm not sure of what percentage.

5. My calculations show that the carbon will be utilized at a
rate of 1.50 ft^3/Million gallons of flow.

6. I have also indicated on drawing M-1 or DP154335 where the
location of the tap should be palced. By placing the tap here,
the water sypply to the carbon system will pass through the green
sand filters and the stripper prior to carbon treatment.

7. Your points of contact are:

At Picitanny
        Plant operator - Roy Oaks   PH 201-724-4151
        Project coordinator - Lynn Krupac PH 201-724-5951

At WES
        Principal Investigator - Mark Bricka   PH 601-634-3700
        Assistant Investigator - Beth Flemming PH 601-634-3943
        Budgeting Office - Val Tomely   PH 601-634-3622

HYDRAULICS   GEOTECHNICAL   STRUCTURES   ENVIRONMENTAL   COASTAL ENGINEERING   INFORMATION
LABORATORY   LABORATORY   LABORATORY   LABORATORY   RESEARCH CENTER   TECHNOLOGY LABORATORY

8. I have attached a copy of the MIPR to this letter for your information.

I will be out of town until 07 SEP 92. If you need any questions to be answered please contact any of POCs provided. Please contact me after the 7th if you have any questions. My number is 601-634-3700.

Thanks for your assistance with this project.

Sincerely,

R. Mark Bricka
Environmental Engineer, P.E.

MILITARY INTERDEPARTMENTAL PURCHASE REQUEST					1. PAGE 1 OF PAGES	

2. FSC	3. CONTROL SYMBOL NO.	4. DATE PREPARED 24 AUG 92	5. MIPR NUMBER W81EWF-2-M193		6. AMEND NO. BASIC

7. TO:	8. FROM: (Agency, name, telephone number of originator)
USAED, OMAHA ATTBl CEMRO-ED-MA, STAN TOLLE 3215 N. 17TH STREET OMAHA, NE 68102	COMMANDER & DIRECTOR USAE WATERWAYS EXPERIMENT STATION, CE 3909 HALLS FERRY RD (ATTN: CEWES-RB) VICKSBURG, MS 39180-6199

9. ITEMS ☐ ARE ☐ ARE NOT INCLUDED IN THE INTERSERVICE SUPPLY SUPPORT PROGRAM AND REQUIRED INTERSERVICE SCREENING ☐ HAS ☐ HAS NOT BEEN ACCOMPLISHED.

ITEM NO. a	DESCRIPTION (Federal stock number, nomenclature, specification and/or drawing No., etc.) b	QTY. c	UNIT d	ESTIMATED UNIT PRICE e	ESTIMATED TOTAL PRICE f
	DISCRIPTION OF SERVICES TO BE PERFORMED: 190 DESIGN AND COST ESTIMATES FOR A PROPOSAL CARBON TREATMENT PLANT FOR THE DRINKWATER AT PICITANNY ARSENAL. Please bring this document to the attention of Mr. Roger Strom, (402) 221-4420. WES principal investigator is Mr. Mark Bricka, CEWES-EE-S, (601) 634-3700. REQUEST THIS DOCUMENT BE ACCEPTED FOR FINANCING ON A AREIMBURSABLE BASIS. PLEASE HAVE ACCEPTING OFFICIAL SIGN DD FM 448-2 AND RETURN TO ADDRESS IN BLOCK 8 ABOVE. EXPIRATION DATE OF FUNDS BEING TRANSFERRED IS 30 SEP 92.				$3,000.00

Certification stamp (handwritten): AVAILABLE FUNDS ARE CERTIFIED AS CITED IN ACCORDANCE WITH ... AS APPLICABLE IN THE AMOUNT OF: 2800.00 200.00 AUG 2 1992 *Elizabeth M Long* ... FINANCE & ACCOUNTING OFFICER R1192m193 R1192m19C

10. SEE ATTACHED PAGES FOR DELIVERY SCHEDULES, PRESERVATION AND PACKAGING INSTRUCTIONS, SHIPPING INSTRUCTIONS AND INSTRUCTIONS FOR DISTRIBUTION OF CONTRACTS AND RELATED DOCUMENTS.	11. GRAND TOTAL $3,000.00

12. TRANSPORTATION ALLOTMENT (Used if FOB Contractor's plant)	13. MAIL INVOICES TO (Payment will be made by) BLOCK 8 ABOVE
	PAY OFFICE DODAAD

14. FUNDS FOR PROCUREMENT ARE PROPERLY CHARGEABLE TO THE ALLOTMENTS SET FORTH BELOW. THE AVAILABLE BALANCES OF WHICH ARE SUFFICIENT TO COVER THE ESTIMATED TOTAL PRICE.

ACRN	APPROPRIATION	SUBHEAD	SUPPLEMENTAL ACCOUNTING CLASSIFICATION	ACCTG STA DODAAD	AMOUNT
	2122040		08-8140 P612784 2572 S220/9 RD2E241E2Q72001 (E5) R1192m193 RD2E260E2Q72001 (E5) R.1192m19C		$2,800.00 200.00

15. AUTHORIZING OFFICER (Type name and title) GLENDA TRAXLER, C/BUDGET BRANCH	16. SIGNATURE *Betty Lou Hughes*	17. DATE 24 Aug 92

DD FORM 448 1 JUN 72

PREVIOUS EDITIONS OBSOLETE.

Appendix J
Capital Cost Estimates for
Carbon Adsorption System

Carbon cost

Data from Appendix G

$$carbon\ usage = \frac{21,791\ lb\ carbon}{year}$$

and a price quote from Calgon (Mr. Chuck Polinski @ 1-800-336-7116) for $0.86/lb for regenerated carbon (including regeneration and delivery) were used to calculate the cost per year for regenerated carbon.

$$\left[\frac{21,791\ lb}{year}\right]\left[\frac{\$0.86}{lb}\right] = \boxed{\frac{\$18,740}{year}\ for\ regenerated\ carbon}$$

The price for virgin carbon, $1.50/lb (Mark Wichman), increases the cost as shown.

$$\left[\frac{21,791\ lb}{year}\right]\left[\frac{\$1.50}{lb}\right] = \boxed{\frac{\$32,726}{year}\ for\ virgin\ carbon}$$

Carbon disposal cost

- Carbon density = 29 lb/ft^3.

- Assume the spent carbon is incinerated.

- Assume incineration cost $200/55-gal drum.

$$\left[\frac{21{,}791 \;\; lb \; of \; carbon}{year}\right] \left[\frac{1 \; ft^3}{29 \; lb}\right] \left[\frac{7.48 \; gal}{1 \; ft^3}\right] \left[\frac{\$200}{55 \; gal}\right] = \frac{\$20{,}438}{year}$$

$$\boxed{\frac{\$20{,}438}{year} \; for \; disposal}$$

Labor cost for plant operation and maintenance

- Assume it will take on the average of 2 hr per day to perform any small-scale maintenance and data collection for the carbon system.

- Assume a plant operator's salary is $30/hr with overhead and burdens.

Thus

$$\left[\frac{365 \; day}{year}\right] \left[\frac{2 \; hr}{day}\right] \left[\frac{\$30}{hour}\right] = \boxed{\frac{\$22{,}000 \; operation \; labor}{year}}$$

From *Perry's Handbook for Chemical Engineers*, pp. 25-27, supervision labor is estimated at 10 percent operating labor.

Therefore

$$\left[\frac{\$22{,}000 \; op \; labor}{year}\right] (0.10) = \boxed{\frac{\$2{,}200 \; supervision \; labor}{year}}$$

$$Total \; labor = \$22{,}000 + \$2{,}200 = \boxed{\frac{\$24{,}200 \; labor}{year}}$$

Pump energy cost

From Perry's Handbook, pp. 6-5:

$$power = HQ\rho/3.670 \times 10^5$$

where

$power = $ kilowatt

$H = $ head, m

Q = flow, m³/hr

ρ = kg/m³

From Table 19, the pump head required is 48 ft.

So

$$H = (48 \ ft) \left[\frac{1 \ m}{3.28 \ ft} \right] = 14.63 \ m$$

and

$$Q = 700 \ GPM$$

So

$$Q = \left[\frac{700 \ gal}{min} \right] \left[\frac{60 \ min}{1 \ hr} \right] \left[\frac{0.0038 \ m^3}{1 \ gal} \right] = \frac{160 \ m^3}{hr}$$

and

$$\rho = \left[\frac{1 \ g}{cc} \right] \left[\frac{1 \ kg}{1,000 \ g} \right] \left[\frac{100 \ cm}{1 \ m} \right]^3 = \frac{1,000 \ kg}{m^3}$$

So

$$power = \frac{(14.63 \ m) \left[\dfrac{160 \ m^3}{hr} \right] \left[\dfrac{1,000 \ kg}{m^3} \right]}{3.670 \times 10^5}$$

$$power = 6.38 \ kW$$

Assume that the pump is only 60-percent efficient and power costs
$0.06/kW hr

$$(6.38 \ kW) \left[\frac{1}{0.60} \right] \left[\frac{0.06\$}{kW \ hr} \right] = \frac{\$0.63}{hr} \ or \ \boxed{\frac{\$5,518}{year} \ for \ power}$$

Backwash water cost

- Assume the maximum flow at one pump is used to backwash @ 700 GPM.

- Assume the need to wash carbon columns once per month.

- Assume water cost is approximately 1.5¢/gal.

- Assume backwashing lasts 30 min.

$$\left[\frac{700 \; gal}{min}\right] \; (30 \; min) \; \left[\frac{12 \; months}{year}\right] \; \left[\frac{\$0.015}{gal}\right] \; = \; \boxed{\frac{\$3,780.0}{year}}$$

Cost summary

Operation and Maintenance	Per year, $
Labor and Maintenance	24,200
Electric Costs	5,518
Backwash Water	3,780

Carbon Replacement
   Regenerated carbon
   Virgin carbon
   Carbon disposal
	
	 18,740
	 32,726
	 20,438

Total for Regenerated Carbon	52,238/year
Total for Virgin Carbon	86,688/year

Appendix L
Capital and Operation and Maintenance Cost Estimates for Ultraviolet/Ozone System

Capital cost estimation for the ultraviolet (UV)/ozone system

(provided by Ted Streckfus, Omaha District)

Using the pilot operating conditions:

> Qwater = 5 gpm
> Retention time in reactor = 3.75 min
> QAir = 190 Scfh
> Ozone concentration = 0.5 percent by weight

a. Develop ozone dosage (input) to reaction vessel:

$$0.5\% \; O_3 \; by \; weight \; equals \; \frac{5 \; lbs \; O_3}{1,000 \; lb \; air}$$

$$190 \; Scfh \; = \; \left[\frac{190 \; Sct}{min} \right] \; \left[\frac{1 \; hr}{60 \; min} \right] \; = 3.17 \; Scfm$$

(1) Convert to mass basis of O_3 using ideal gas law

$$\left[\frac{5 \; lb \; O_3}{1,000 \; lb \; air} \right] \left[\frac{3.17 \; sct}{min} \right] \left[\frac{28.98 \; \frac{lb}{lb \; mole}}{359 \; \frac{ft^3}{lb \; mole}} \right]$$

$$= \frac{0.0128 \; lb \; O_3}{min} \; Standard \; conditions$$

or

$$\frac{1.84 \; lb \; O_3}{Day}$$

(2) Convert to milligram basis

$$\left[\frac{0.00128 \; lb \; O_3}{min} \right] \left[\frac{454 \; g}{1 \; lb} \right] \left[\frac{1,000 \; mg}{1 \; g} \right] = \frac{581.1 \; mg \; O_3}{min}$$

(3) Based on the flow rate through the reaction vessel, calculate the ozone dosage (input) to the water

- Convert to liter/minute

$$Flow = 5 \; GPM = \left[\frac{5 \; gal}{min} \right] \left[\frac{3.784 \; \ell}{gal} \right] = 18.92 \; \frac{\ell}{min} \; Flow$$

- Calculate O_3 concentration in water fed to reactor

$$\frac{581.1 \; \dfrac{mg \; O_3}{min}}{18.92 \dfrac{\ell}{min}} = 30.7 \frac{mg}{\ell} \; O_3 \; to \; reactor$$

(4) Calculate use of O_3 per day in a 1 MGD plant

$$8.34 \; QC = M$$

$$\left[8.34 \frac{lb/mg}{mg/\ell} \right] (1 \; MGD) \left[30.7 \; \frac{mg}{\ell} \right] = 256 \; \frac{lb \; O_3}{day}$$

This would necessitate a 300 lb/day O^3 generator.

b. Calculate the required reactor site based on retention time; Jack Zeff of Ultrox, a division of RCC (714-545-5557), suggested for scale up, Ultrox, uses a 1:1 ratio.

Thus for a DT of 3.75 and a 1 MGD plant

$$(3.75 \text{ min}) \left[\frac{1 \times 10^6 \text{ gal}}{day} \right] \left[\frac{1 \text{ day}}{24 \text{ hr}} \right] \left[\frac{1 \text{ hr}}{60 \text{ min}} \right]$$

$$\boxed{= 2,604 \text{ gal capacity}}$$

c. *Capital cost for UV/ozone reactor.* Based on the DT of 2,604 gal, a standard Ultrox model F-2600 is recommended.

Per Jack Zeff at Ultrox, F-2600 costs are as follows:

Capital expense = \$510,000 line, which includes:

(1) O_3 generator

(2) Air prep system.

(3) Compressors.

(4) Catalysts bed.

(5) UV reactor.

This cost does not include installation.

- Assume 15 percent of the capital cost for installation, 6 percent SIOH (supervision, inspection, and overhead), and 10 percent contingency

Capital cost = 510,000

- installation = (510,000)(0.15) = 76,4500

$$\boxed{\text{capital + installation} = 586,500}$$

- add contingency (586,500)(0.10) = 58,650

capital + installation + contingency = 586,500 + 58,650
= 645,150

- add SIOH = (645,150)(.06) = 38.709

$$capital + installation + contingency$$
$$+ SIOH \text{ for } UV/ozone \text{ sytem only } = \$683,859$$

d. *Capital support costs.* Assume the footprint for the UV/ozone system is the same as the carbon system, and the UV/ozone system will require similar support except for electrical (from Appendix K).

(1) A 30- by 30- by 1-ft concrete pad = $\$13,414.$

(2) Two centrifugal pumps at 700 gpm and 48 ft of head = $\$24,471.$

(3) 35 ft of 10-in. pipe = $\$3,478.$

(4) Building (enclosure) = $\$200,000.$

More electrical support will be required for the UV/ozone system. Assume $15,000 additional electrical thus (from Appendix K)

Electrical = 765

Additional = 15,000

Total electrical = 15,765

e. *Summary for capital expense.*

Concrete pad	13,414
Feed pumps	24,471
Piping	3,478
Electrical	15,765
UV/ozone system	683,859
Building	200,000
Total Capital	$940,987

Annual O&M costs for the UV/ozone system

Per discussions with Ultrox (Jack Zeff), anticipated operational expenses for the F-2600 are estimated at $0.23/1,000 gal of water treated.

This can be divided into

    a. Power for the O_3 = $0.15 = 66%.

    b. Power for the UV   = $0.03 = 13%.

    c. Lamp replacement and other maintenance = $\underline{\$0.05}$ = 21 percent.

    d. Total   = $0.23.

and power is 79.3 percent of the total per Zeff.

A 1 MGD plant

$$\left[\frac{1 \times 10^6 \ gal}{day}\right] \left[\frac{\$0.23}{1,000 \ gal}\right] \left[\frac{365 \ days}{year}\right] = \boxed{\$83,950/year \ total}$$

Total power =

UV power cost = (83,950)(0.13) = $\boxed{\$10,910.}$

O_3 power cost = (83,950)(0.793) - 10,910 = $\boxed{\$55,662.}$

Lamp replacement = (83,950) - (83,950)(0.793) = $\boxed{\$17,377.}$

Electrical estimates must also be supplied to run the pumps (from Appendix J). The pump electrical requirement is

Pumping electrical = $5,518/year

$$\boxed{\text{Total O\&M} = \$89,467/year}$$

Appendix M
Capital and Operation and Maintenance Cost Estimates for Ultraviolet-Only System

Capital cost for the Ultraviolet (UV)-only system

Per Jack Zeff at Ultrox on 18 January 1993, if an O_3 generator is not required, the capital cost of the UV reactor will be reduced by half.

Thus reactor cost is

$$\frac{\$683,859}{2} = \boxed{\$341,930 \; per \; reactor}$$

The electrical support for the reactor will also be less; assume $5,000. Therefore, the total electrical is

$$\$5,000 + \$765 \; (pumps) = \$5,765 \; electrical$$

All other capital costs remain the same.

Summary

Concrete pad	13,414
Feed pumps	24,471
Piping	3,478
UV system	341,930
Electrical	5,765
Building	200,000
Total capital for the UV-only system	$589,058

Annual O&M costs for the UV only system

All costs will be the same as the UV/ozone system except for electrical, which will have no O_3 electrical component:

UV power costs	$10,910
Lamp replacement and maintenance	$17,377
Pumping electrical	$5,518
Total O&M for UV only	$33,814

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11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Past military operations have resulted in the contamination of soils by munitions such as Research Department Explosive (RDX), High Melting Explosive (HMX), and TNT. The migration of water through these soils can transport these contaminants into groundwater. Many military munitions are known or suspected to be carcinogenic, and their presence in groundwater may pose a public health risk if the groundwater is used as a drinking water source.

This reports details the removal of low levels of RDX and HMX from drinking water sources located at Picatinny Arsenal near Dover, NJ. This report details the use of carbon as a treatment alternative. In a separate report entitled "Ultraviolet/Chemical Oxidation Treatment of RDX-Contaminated Waters at Picatinny Arsenal," the use of ultraviolet/chemical oxidation treatment for the same groundwater is detailed.

Typical levels of RDX and HMX measured in the drinking water ranged from 4 to 6 parts per billion (ppb) and 1 to 3 ppb, respectively. Current health standards are above these limits, but it is expected that these limits will be substantially reduced in future years. In anticipation of stricter standards for RDX and HMX in drinking water, this study was initiated to investigate the removal of RDX and HMX using carbon adsorption technologies. Five carbons were evaluated using batch isotherm tests. Based on these isotherm tests and economic factors, Calgon's Filtrasorb-200 (F-200) and American Norit's Hydrodarco-4000 (H-4000) were selected for detailed column studies.

(Continued)

14. SUBJECT TERMS

See reverse.

15. NUMBER OF PAGES
163

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13. (Concluded).

Pilot carbon column studies were conducted onsite at Picatinny Arsenal during the period of August 1991-August 1992. Based on the results of this study, it was determined that both carbons performed well, with both carbons having a high sorption capacity for RDX and HMX. Based on this study, it was found that the F-200 and H-4000 utilization rates were 2.05 and 1.99 ft^3 (0.058 and 0.0563 m^3) of dry carbon per 1 million gal (3,785,000 ℓ) of drinking water treated, respectively.

14. (Concluded).

Army
Carbon treatment
Contamination
Design
Drinking water
Explosive
Granular activated carbon
Groundwater
HMX
Low-level removal
Picatinny Arsenal
RDX
Sorption
Water supply